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Vertisolic soils under agroforestry in north east Nigeria

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Award date:
1998

Awarding institution:
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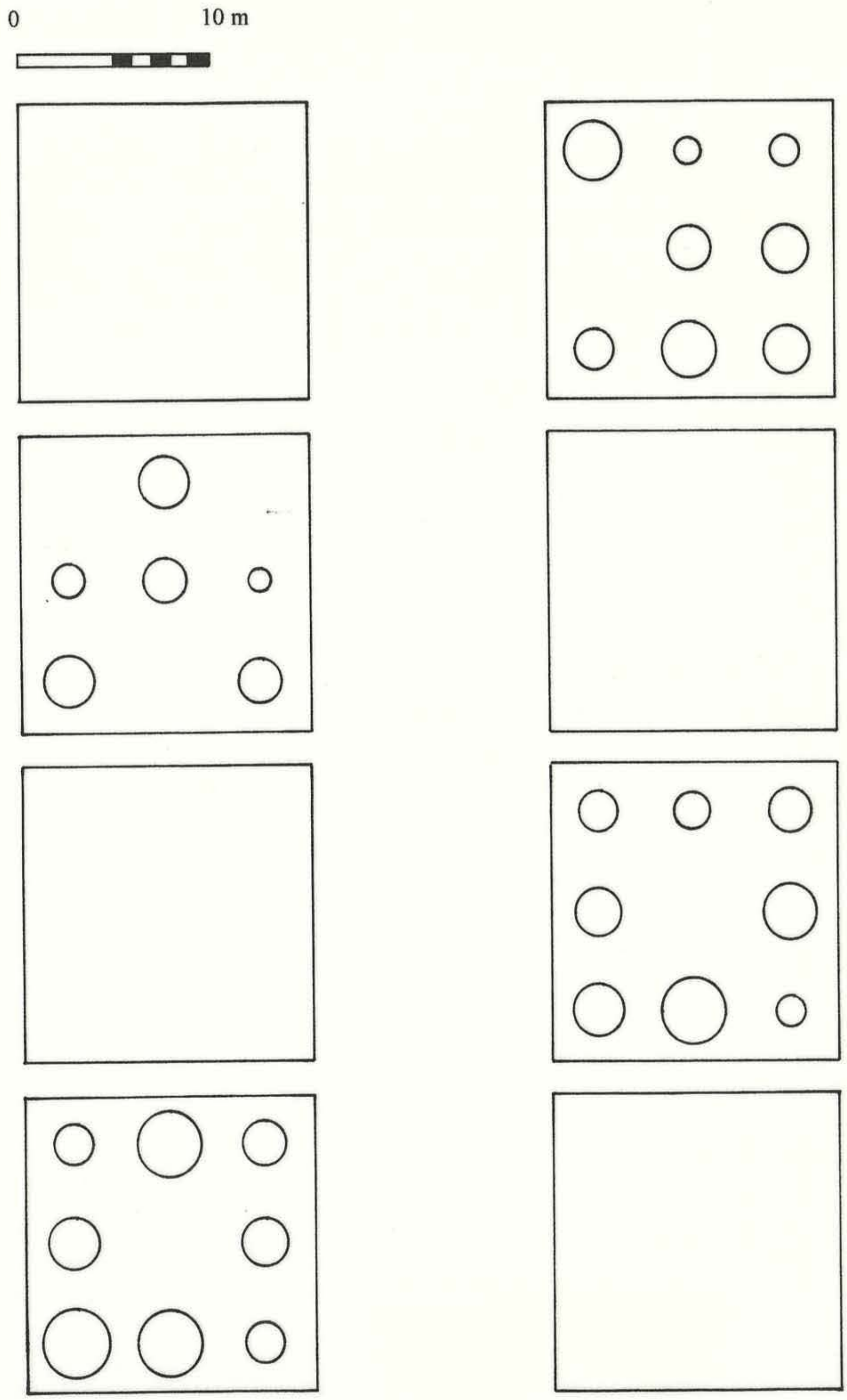
Vertisolic soils under agroforestry in North East Nigeria

Paul Adderley
University of Wales, Bangor
PhD 1998

Copy of Figure 5.24
Tree canopy size overlay for figures 5.18 - 5.23
(February 1994 - canopy measurements)



Vertisolic Soils under Agroforestry in North East Nigeria

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Vertisolic Soils under Agroforestry in North East Nigeria

Summary

Deteriorating environmental conditions are being experienced by farmers in the Sahel region with the lacustrine clay plains, south of Lake Chad, experiencing extensive changes as the lake area has contracted. Coupled with increased population pressures, these are driving the agronomic experimentation in this region. The objective of the work undertaken in this thesis has been to characterise the development, physical and nutrient status, within the soils found under an experimental agroforestry system. For the first time in semi-arid Africa, this has been accomplished over a range of spatial scales (*i.e.* plot (<25 m) - site (25-200 m) - region (<200 km)), and is a baseline for future studies.

At the regional scale, pedogenesis in four profiles was examined. Field observations of physical soil characteristics (cracking, gilgai) were consistent with a chronosequence of exposure from Ustic Aquepts to Usterts. In more detailed measurements, pedogenic trends were masked by the heterogeneity of the parent materials.

At the plot (320 samples) and site (480 samples) levels, the measurements of chemical (Tot N, Tot P, OM, pH, EC, Loi, %$CaCO_3$) and physical (BD, texture, microtopography, penetration resistance, soil structure by image analysis, depth of sand layer, colour, infiltration) variables were analysed statistically, including principal component analysis to produce a summary variate, and by geostatistical techniques producing semi-variograms. A trend across the site in soil texture (% sand, silt, clay, fine clay) was mirrored by other parameters (pH, EC, Loi, microtopography) suggesting that the surface soil chemistry is dominated by the overlying aeolian sand layer. Significant ($P<0.05$) effects of tree planting were revealed at the plot level, in the image analysis of soil structure measurements and in the subsequent infiltration on sandy sites.

The soil-structure differences found under agroforestry are seen to be developing in parallel with natural pedogenesis and are expected to become more pronounced as the trees mature with increased organic input and physical interaction between trees and soil. Whilst general trends are found in site level measurements, at the plot level a variable heterogeneity is found. For local farmers the management of this variability is paramount to overcome the marginal climatic conditions for rain-fed cropping whilst researchers must either consider longer time periods for soil changes to become apparent, or undertake sampling at greater density at the smaller scales.

Acknowledgements

I would like to thank the many people who have supported me during the course of this work, particularly my supervisor Dr David Jenkins and the soil science staff at the University of Wales, Bangor. I also pay special thanks to those people who have assisted me so much in the field work in Nigeria and in the logistical support in the UK for such to be completed: Project Management from Profs. I. Verinumbe and W.S. Richards - University of Maiduguri - and Dr F. Sinclair with secretarial support from Karen Cooper - University of Wales, Bangor. This project (R4850) was supported financially by the Forestry and Agroforestry Research strategy programme of the UK Overseas Development Administration. Thanks are directed toward my colleague Dr V. Grime and her husband Ali Nouhou for their persistence and help in Nigeria and to all the staff of the Department of Biological Sciences, University of Maiduguri for their support and good humour.

It has been most gratifying to have received excellent technical help throughout this project. In Nigeria, Christopher Nutchwuku has been of tremendous help; in the UK special thanks are reserved for the late Hilton Trow, soil science technician, who will be fondly remembered. Thanks also to the faculty workshop team of Bernard Tilley and Alun Jones.

Many people have given specific advice or provided invaluable help: Dr Liz Fellman of British Geological Survey for the chemical analysis of water samples; Drs. Bridget Emmett and Lloyd Anderson of the Institute of Terrestrial Ecology, for discussing nutrient cycling and ecophysiological interactions respectively; Dr Geoff Nwaka of the University of Maiduguri for help in the pedological description of vertisolic soils and Barbara Zach and Holger Kirscht of Goëthe Universität of Frankfurt am Main for their assistance in botanical identification and interpreting local soil names respectively. Special thanks for their help, warmth and encouragement are given to Sara Rowland for checking tree-data entries, Dr Donald Marshall for proof-reading; Patricia Adderley for cross-checking reference entries and to Dr James Roger of Live Data Process for his SAS programming advice and expertise in the analysis of statistical information. To have gained many friendships during the course of this work has been especially rewarding.

Finally, special thanks to my parents for their kindness and patience throughout the completion of this work.

Dedication

This work is dedicated to the memory of my grandfather, Arthur Jones.

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1 INTRODUCTION

1.1 Introduction and theme of this thesis

Many inter-related factors determine the development of soil at any particular location. These factors vary both spatially and temporally, thereby creating the variety of soils seen world-wide. Whilst many attempts have been made to identify the relationships between these factors, their combination at any particular location will be manifested as the resulting soil (Jenny, 1941). At a simplified level, soil can be seen as a component in dynamic equilibrium with a variety of natural components.

Man's activities, particularly the development of agriculture, have disturbed this equilibrium. By introducing practices which operate in short time periods, these activities, if poorly managed, may cause severe disruption, leading to a deterioration of the soil; for example the collapse of soil structure, or salinization, or desertification. Degradation of soil and of land is most likely to occur at locations where the equilibrium is fragile and prone to disruption, such as where human populations have rapidly increased. Such areas are often termed marginal and the population of these areas considered marginalised (Blaikie, 1985). Lately, it has been realised that soil and land degradation is occuring on large scales, both in terms of the finite amount of land surface affected and in terms of changes at one location affecting another, often distant, location. Such environmental deterioration, accelerated or compounded by human actions, is currently a subject of much debate world-wide and is often addressed in political and ideological terms rather than through scientific methodologies.

Where actions attempting to remedy such deterioration have been implemented, they have often been prescriptive rather than derived through scientific rationale. Much research, however, is currently being undertaken in a variety of environmental technologies. One such technique is that of agroforestry.

This thesis addresses these broad issues as two related themes. Firstly, there is an investigation of the factors influencing the development of soils in a land region where agricultural production is currently marginal, the Chad basin. This area is particularly interesting, since it is at the southern fringe of the Sahel, supports an expanding population and has soils which are relatively young. Secondly, the development of soils in this region, particularly the development of soil structure, is placed within the context of agroforestry research. This part of the work focuses upon a specific agroforestry research field site at New Marte in North East Nigeria.

The relatively young soils in this geographic region should show stronger observable contrasts between the effects of the various natural processes influencing the area than would be expected on older, more developed soils. On the agroforestry field-site such pedogenic factors are compounded, in the short term, by the effects of trees, which in turn induce other biotic-soil interactions. The processes occuring at the field site have therefore been considered temporally within a sequence of other soils examined across the region. This provides contrasts between the soils and also between the factors influencing their development.

1.2 THE NEED FOR RESEARCH?

1.2.1 The nature of the problem

Ecosystems in semi-arid regions throughout the world are subject to both natural and anthropogenic stresses. The developing world encompasses the majority of semi-arid lands and the population increases that have already occurred have led to an increasingly unsustainable use of land resources. In the late eighteenth century the English political economist Thomas Malthus commented:

> Population, when unchecked, increases in a geometric ratio. Subsistence only increases in an arithmetic ratio.
> *Essay on the Principle of Population, Ch. 1, 1798*
> (Malthus, 1798)

This Malthusian reasoning, comparing population with resources, has been held as the central tenet of much of the work undertaken where development issues have been considered. Such development work may be undertaken on a small scale (*e.g.* Chleq & Dupriez, 1988) or may take the form of large scale multi-government initiatives such as those addressed or initiated in the so called "Brandt Report" (Independent Commission on International Development Issues, 1980) and at the 1992 "Earth Summit" (Johnson, 1993). Since Malthus there has been a series of philosophies on the issue of land degradation and resource mismanagement, particularly when the relative success or failure of initiatives undertaken in the post 1945 period have been reviewed. Apart from reiterations of the Malthusian line of reasoning and some subtle modifications (*e.g.* a Ghandian approach - Barrow, 1991), there are several additional viewpoints. Most common are the economic arguments, ranging from a consideration of tenure issues (*e.g.* Durning, 1993) to resource management favouring short-term exploitation regardless of unknown long-term consequences (Pigou, 1924 and Dobb, 1937, *ibid.*, 1946). This issue has more recently been popularized (*e.g.* Adlard, 1993) through the concept of "sustainability", which has been lauded as a global aim when defined as "the ability to meet the needs and aspirations of the present without compromising those of the future" (World Commission on Environment and Development, 1987). A somewhat cynical view which has gained recent popularity is that external factors, such as inappropriate aid or technology transfer, have created a dependency on further aid in the recipient area (Bauer, 1981). Another development has been attempts at an economic quantification of natural resources, famously by "The Club of Rome" (Meadows *et al.*, 1972), and in a recent review by Kula (1994). It has been argued (*e.g.* Price, 1984) that, in circumstances where resources are intensively exploited and non-renewable, the reliance on future technological advances should not be used in the construction of an economic argument in favour of development. Several authors, principally in review works such as by Barrow (1991), have synthesised a new position. In a recent review considering land degradation, Blaikie and Brookfield (1987) extended the Malthusian argument, equating net degradation to natural degrading processes and human interference, minus natural reproduction and restorative management. The current thesis is concerned with the soil-oriented aspects of one such possible restorative management technique: agroforestry.

1.2.2 Present evidence of the problems of managing marginal lands

Regardless of the academic argument used to define the cause of the problem of resource mis-management, there is now a large body of evidence (*e.g.* FAO, 1976; Advisory Committee on the Sahel, 1984; McCarthy, 1992; World Bank, 1991) that certain land areas of the world are under special and increasing pressures due to human activity. In these areas land degradation is occurring most rapidly and have come to be known as *"marginal"*. They are of poorer quality than the majority and possibly susceptible to mis-use and in many cases chronic degradation (Barrow, 1991). Land degradation is especially significant in the semi-arid regions, since they have the greatest climatic vunerability to erosion, and also the pressures are becoming greater and land reclamation can often only be achieved over long time periods, if at all. Whilst natural phenomena, such as rainfall and wind, can be the cause of land degradation, it is human activities which accelerate the process and are therefore seen to cause most damage. Such activities include the removal of trees for fuelwood (Arnold, 1992) and overgrazing (Barrett, 1989). This has led to some authors, such as Johnson and Lewis (1995), to use the term *"land degradation"* only when human interference has caused the decline in quality.

Whilst there have been many discussions of the problem in terms of general resource mis-use, normally relating this to population growth, there has not been a focussed debate of soil issues. The removal of soil by wind erosion came to great prominence in the 1930's when the *"dust bowls"* developed in the central United States (Colorado, Kansas, New Mexico, Oklahoma and Texas). These were well documented by many authors (*e.g.* Jacks and Whyte, 1939 and, more recently, Worster, 1979) and resulted in the creation of the United States Soil Conservation Service and a major expansion of soil science research world-wide (Council for Agricultural Science and Technology, 1982). In the same period as the American dust bowls, two wide ranging and extensive reviews were undertaken in the British Empire. Both Stockdale (1937) in the review, *Soil Erosion in the British Empire,* and Hailey's *African Survey* (1938), paid great attention to the problems of soil erosion and to more general soil degradation. The problems of soil degradation were therefore recognised in the mid to late 1930's and were still prominent during the immediate post-1945 period. However, during the 1960's, particularly in the former colonies of European nations, political awareness of the problem waned, leading to many incidents of poor land and soil management. Young (1989) considers that this was due, in part, to the rejection, in the newly independent countries, of ideas that had been implemented by the colonial services. In Northern Nigeria the [British] Colonial Service had been aware of soil erosion problems, particularly in heavily populated areas (McClintock, 1992). Kimmage (1990), in respect to the occurance of soil erosion problems, recently made a comparison between the situation in the United States of America in the 1930's and that of present-day northern Nigeria.

1.2.3 Soil degradation

Degradation of land may be due to many different factors, some of which will be interrelated with one-another; for instance, insect swarms destroying vegetation and so leading to greater wind or water erosion. When the view of the problem is narrowed to focus solely upon soil degradation, these factors may be categorised as either erosive or non-erosive. Therefore, in this thesis the definition of soil erosion stated by Kirkby and Morgan (1981) will be used: "the physical movement of individual soil particles by wind and water". This needs to be stated in order to avoid an unfortunate confusion in terminology which has arisen: in some discussions (*e.g.* Hudson, 1971, Blaikie, 1985) soil erosion has been considered to include any degradation of the soil whereby its ability to sustain and produce crops is diminished.

Whilst soil erosion is directly caused by the natural agents of wind and water, in cultivated land it is the culmination of poor management. It may be controlled to a rate approximating natural conditions by good management of cultivation. The most damaging cases of soil erosion occur where the largest expanses of land are subjected to the worst kind of management in areas where natural forces such as rainfall have their greatest impact. Such areas tend to be the semi-arid areas with a maximum erosion loss at a mean annual precipitation of 300 mm (Langbein and Schumm, 1958). Areas with lower effective precipitation suffered less but erosion increased with precipitation, whereas areas with more than this amount of precipitation had greater vegetation surface cover and so suffer less erosion. However, there is some more recent evidence that areas with much greater quantities of rainfall experience even more intense erosion (Gregory and Walling, 1973). These two models are shown in figures 1.1 and 1.2.

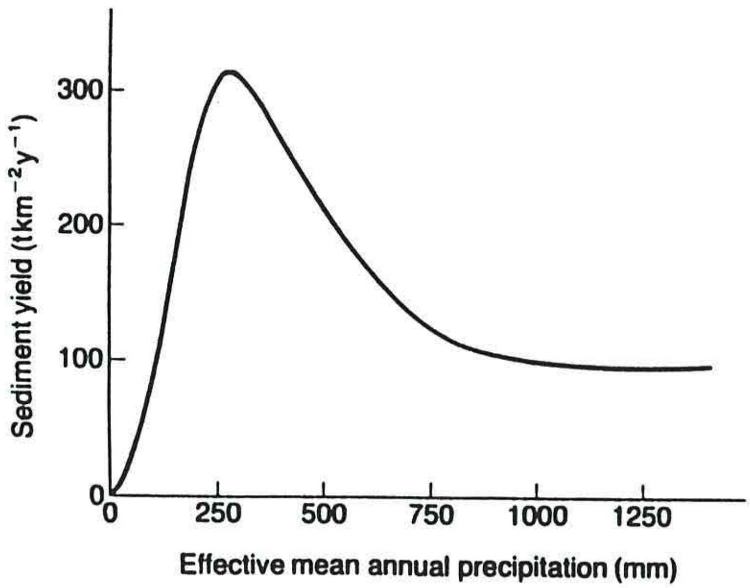


Figure 1.1 - Proposed relationship between Effective mean annual precipitation and sediment yield (Morgan, 1986 after Langbein and Schumm, 1958)

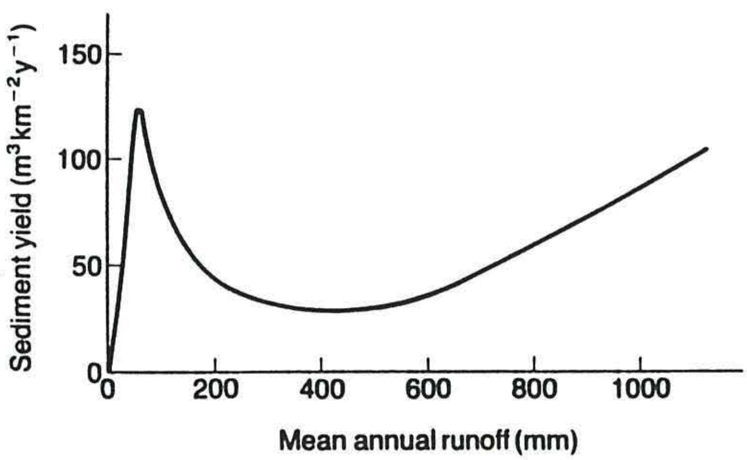


Figure 1.2 - Proposed relationship between mean annual runoff and sediment yield (Morgan, 1986 after Gregory and Walling, 1973)

There have been many attempts to quantify soil erosion. Apart from direct measurement of losses from a specific location, there are several other approaches. The measurement of sediment loads in areas where there is run-off into water courses is one method, but this is flawed when estimates from anything less than the total catchment are required, which in turn pre-supposes that the catchment can be defined. Another possibility is to use a reasonable surrogate as an estimator. One of the most frequently cited methods is the Universal Soil Loss Equation, which is used to predict the loss of soil by the action of water. This method has been used by many authors for the Sahelian region (*e.g.* Unger, 1984) despite the fact that its fundamental paradigm is based on that of a mid-belt United States agrarian landscape. It considers a number of factors, both relating to the site (rainfall, soil, slope) and to management (vegetation cover, conservation practice). A similar equation has been constructed for wind erosion (Hudson, 1981 - quoted by Blaikie, 1985). There are many difficulties in applying these models to areas where there is a lack of the detailed information required to quantify each one of the factors used in the equation. Yet another approach is to extrapolate an index of erosion derived from short-term applied experimentation. This may either be *in situ,* for example the measurement of precipitation impact or wind erosion (*e.g.* Greenland and Lal, 1977; Scott, 1995), or be laboratory orientated, for example simulations of rainfall (*e.g.* Lavee *et al.*, 1991, Dunne, 1977) or of wind-action on a representative soil sample.

An endpoint of soil erosion in the semi-arid regions is the desertification of the land, where the land cannot support a plant community to the extent of economic production even when other factors such as rainfall are conducive. Whilst some economic thinking treats soil as a non-finite resource that can be continually exploited (*e.g.* Simon, 1981), there is a general unanimity amongst soil scientists and governmental bodies that soil erosion is a major problem (*e.g.* FAO, 1977; Morgan, 1986; Johnson, 1993; Pimentel, 1993; Wild, 1993). It is therefore important that strategies to prevent or minimise erosion are adopted.

Whilst soil erosion is frequently seen to be the source of all soil degradation, there are a variety of other degrading factors which, anthropogenic or otherwise, should be considered. These have been termed "non-erosive soil degradation" by Barrow (1991). Apart from pollution by extraneous materials such as radio-nucleotides (*e.g.* FAO, 1989) or heavy metals, these factors involve physical or chemical damage to the soil which is deleterious to the subsequent growth of plants. They include salinization, alkalinization, waterlogging, and soil structural changes. The last may be due either to compaction or to changes in the chemical status of the soil. Changes in soil structural stability are particularly significant in the current study, since the effect of changes in the quantity of organic materials on the structure and fabric of the soil are a key element of the central hypothesis (see section 1.3.3 later) of the experimentation.

1.2.4 Potential remedies to soil degradation

Whilst the nature of the problems of land and soil degradation continue to become more clearly defined, particularly in terms of issues of global significance (*e.g.* Brady, 1994, Goudie, 1993), many authors continue to address the issue by relating to the humid tropics (*e.g.* Sanchez & Anaya Garduño, 1994), ignoring the semi-arid areas. Whilst there is no doubt that the effects of human population, rainfall and vegetation removal, acting on these humid areas can be much greater *in toto*, the impact of the human population in semi-arid or arid zones are relatively just as destructive. There is growing recognition that the semi-arid areas have been ignored in this way for much of the period of agricultural development (Blaikie, 1985) and that the population of these areas can become marginalized. This occurs both in the initial adoption of unsustainable land practices and then in attempts to alleviate or rectify this situation. Many different strategies for remedial treatment have been proposed. These have ranged from projects involving large amounts of human intervention and capital input into technologies such as irrigation schemes through to the simplest, for example, minimising human involvement in an area through the demarcation of a nature reserve or conservation zone. Latterly, the use of high technology methods has waned, and prescribed solutions to the general problems facing these regions have become focussed on the preservation or re-introduction of trees. "Trees are good!" would appear to be the crudest form of the development message.

In the development of remedial methods, greater attention has again been placed on the humid tropics. In current vogue is the development of alternatives to "slash and burn" cultivation systems (Okigbo, 1984; Sanchez and van Houten, 1994). Slash and burn is a type of shifting or "swidden" cultivation. These methods have long been recognised as being potentially unsustainable; if land is brought back into cultivation too soon, such that the land has been unable to regenerate fully, then the balance of the cycle of cropping will be upset and the consequent loss of organic matter will reduce the soil's fertility (Nye and Greenland, 1960). Such occurances are normally thought to be due to increasing human population pressure. It has been considered that where such rotational agricultural systems have been retained at a sustainable level they represent an early kind of agroforestry with a temporal, rather than the more usual and easily recognised spatial, arrangement of the tree and crop (Nortcliff, 1992).

In stategies to prevent further extensive land degradation and soil degradation, or to restore land already damaged, agroforestry is seen to play an important rôle in semi-arid regions (Steppler and Nair, 1987). The 1992 "Earth Summit", whilst embracing a variety of technologies to promote sustainability, specifically mentioned and supported the use of agroforestry in order to alleviate land degradation (Johnson, 1993). Prinsley and Swift (1987) edited a review of the ameliorative effects of trees upon soil processes in many different management strategies, amongst which was agroforestry. Lungdren and Nair (1985) and Young (1989) have proposed many different strategies in which agroforestry can be used to control or alleviate problems of soil degradation.

1.2.5 The relevance of the proposed remedies for soil and land degradation

Whilst much of the primary research into agroforestry systems has been undertaken in the humid areas (*e.g.* Woomer & Swift, 1994, TBSF, 1992, Nair, 1989), there is a growing recognition that these systems may also be implemented in the semi-arid areas. It would appear that much of the effort being put into the development of sustainable agricultural systems in the sub-saharan semi-arid area is as a response to the prolonged drought that occured across the Sahelian region in 1967-1973 and less severely in 1983-1984 (Mortimore, 1989). In this region the population pressure is seen as a potential cause of irrevokable land degradation, *i.e.* desertification. Such changes are considered to have considerable long-term impact on the climate of more northerly latitudes also (Council on Environmental Quality, 1982).

In common with many studies of resource management research the most popular current paradigm for agroforestry experimentation is that of "systems and processes" (Anderson *et al.*, 1992). There is a long history of process research; that plants respond to environmental conditions, and that different plants have different responses to above- and below-ground interference was recognised in the experiments performed by Stephen Hales (1727). Whilst there have been many subsequent advances in the understanding of plant and crop physiology, the intercropping of crops and trees as an agroforestry system has only recently become of widespread interest and intensely studied.

It is the application of agroforestry as a farming technique in an area of marginal land productivity, coupled with the human needs mentioned above, that has made the research described here so compelling.

1.3 AIMS AND OBJECTIVES

1.3.1 Aim of this work

The aim of the work described in this thesis is to characterise and produce a detailed account of the pedogenesis and dynamic nutrient status within the soils found under an experimental agroforestry system at New Marte in North East Nigeria. This was set in the context of a chronosequence of a defined range of soils found on the lacustrine deposits of the Chad Basin.

1.3.2 Objectives

The first objective has been the construction of a detailed account of the soils found at and adjacent to the agroforestry experimental area. This has included many aspects: detailed characterisation of the soils found at the experimental site; examination of nutrient turnover processes; description of soil structural characteristics; correlation of water infiltration measurements with soil structural parameters. Incidental to this account is the application of newly available techniques of analysing and presenting such data.

The second objective has been to consider the characteristics of the soils of New Marte in relation to the soils found at other locations in North East Nigeria. These soil descriptions all together have been considered as a chronosequence.

The final objective, drawing these themes and other subsidiary topics together, is an examination of the relationship of all of the soil measurements made within the wider context of primary agricultural production, particularly agroforestry practices.

The aim and objectives of this thesis are set against a background of work undertaken under the auspices of two linked Overseas Development Administration (ODA) projects:

Project R4850

Evaluation of planting spaced trees in cultivated fields on vertisolic soils under low rainfall, with special reference to soil conditions and crop yield

Project R4858

Productivity of intercropped sorghum in relation to water and nutrient stresses in semi-arid agroforestry

These have provided the facilities for almost all of the fieldwork undertaken. The overall broad hypothesis of research taking place in the current phase of ODA experimentation in Nigeria has been:

> " Biomass inputs from trees will improve soil structure and soil fertility. This improvement leads to an increase in infiltration and penetration of water leading to greater water and nutrient uptake by associated crops, thereby producing greater and more sustainable crop and tree productivity. It is implied that the trees will not use more water than their ameliorative effect adds to the system."
> (ODA Project R4850 proposal, 1992)

The research undertaken to investigate and quantify the expectations of this hypothesis has formed part of the work found in this thesis. The hypothesis was tested in a series of nine intermediate objectives, of which three had a major soil science component and are relevant to this thesis:

a) To evaluate effects on physical and chemical soil properties, including water infiltration and penetration, of maintaining high densities of selected indigenous tree species on cultivated land.

b) To evaluate quantitatively the competitive effects of the same trees on water and nutrient use in an integrated tree-crop system, comparing water use efficiency of individual components and the system as a whole with monocultural alternatives.

c) To evaluate the impact of managing tree leaf area through pruning on water use (see b) above), nutrient release, tree and crop productivity and soil characteristics.

1.4 GEOGRAPHICAL LOCATION OF FIELD WORK

A series of sampling sites have been examined in this thesis. This section defines the locations of these sites geographically and indicates the type of work undertaken at each site.

1.4.1 Geographical location and maps

The sites studied in this thesis are all located within North East Nigeria. The work has focused particularly upon a region to the South and West of Lake Chad. This area falls within the political boundaries of Nigeria, more precisely those of the current (1995) Borno State. Despite mixing political and geographical terms, it seems appropriate for the purposes of this work to use the term North East Nigeria to describe the area under consideration. The field sites sampled and the locations of the major towns and cities relative to these are shown in figures 1.3 - 1.4. All of the agroforestry research has been undertaken at a planted experimental site located at New Marte, whereas soil characteristics have been studied at the other locations.

Figure 1.3 Location of region of interest relative to political boundaries

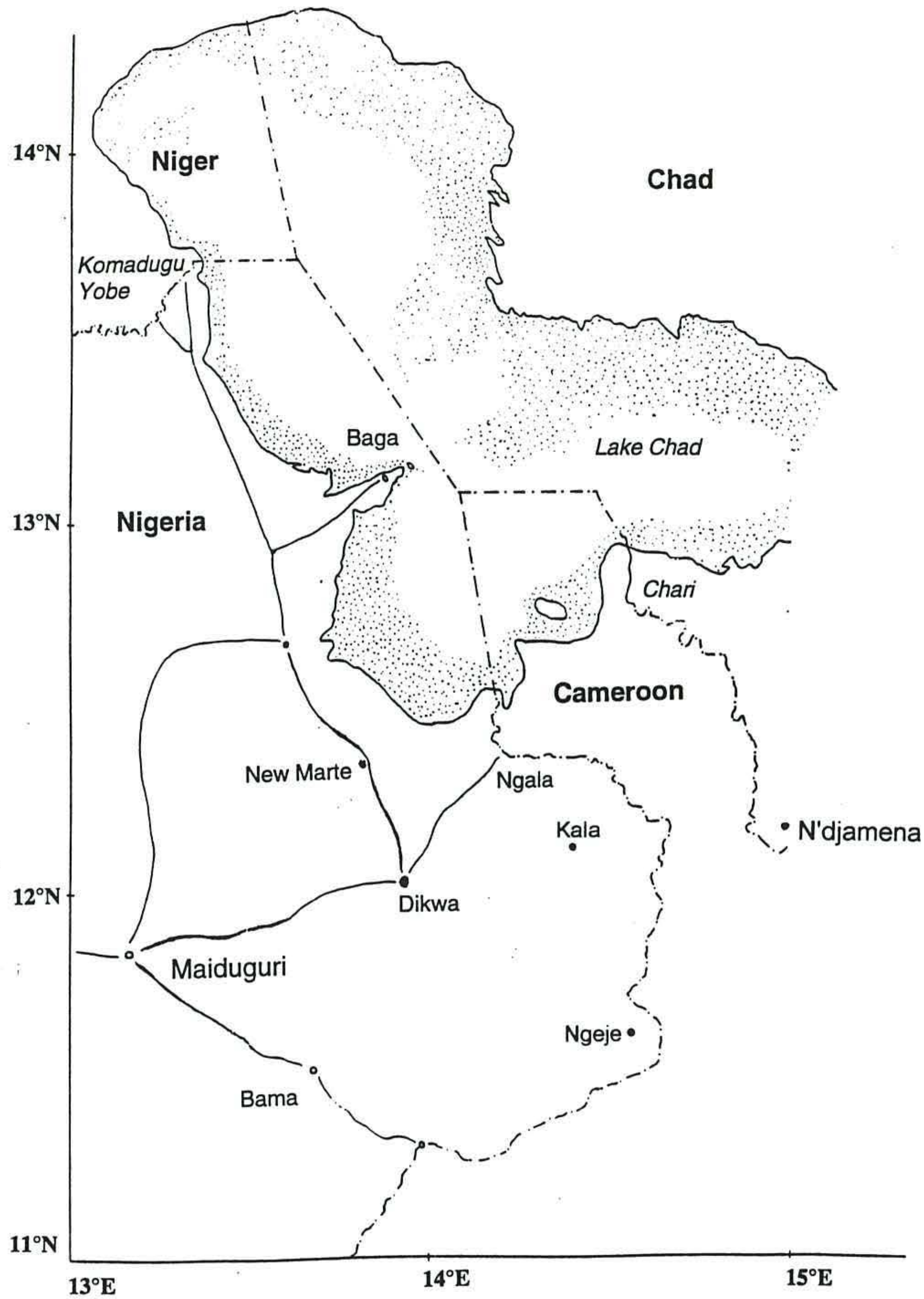


Figure 1.4 Location of field sites in NE Nigeria

The two major cities of this region are Maiduguri and N'Jamena, the latter the capital city of Chad and formerly known, in the French colonial era, as Fort Lamy. These cities act as two hubs to a series of trading routes radiating through Niger, Chad, Sudan and Cameroon. The social and cultural aspects of the communities that live in or use the area have been studied with growing intensity by European researchers (*e.g.* Jungraithmayr & Nagel, 1991). Of special concern are the inter-relationships between different users of the land, a significant minority of whom are migratory pastoralists (Hall, 1991; Le Houérou, 1989).

1.5 METEOROLOGICAL INFORMATION

Despite increasing interest, due in part to studies on the effects of oceanographic fluctuations such as El Niño, there are very few sources of reliable meteorological information available for the Sahelian region. The FAO (1984) agroclimatological reference text cites information from two stations located near to the main sampling site at New Marte (12.25°N 13.87°E). One is at N'djamena (12.08°N 15.02°E). The second is at Maiduguri (11.51°N 13.05°E) in Nigeria. Whilst these stations are located considerable distances away from New Marte (c.120 km and 150 km respectively; see figure 1.4), they provide the only reasonable comparison to longer term records for the measurements made at New Marte. The meteorological data presented in the following sections for Maiduguri and N'djamena respectively represent mean values for the periods 1916-1977 and 1951 - 1978.

1.5.1 Rainfall

The total amount of rainfall in the region is the single most important factor in the production of crops. The frequency and the temporal distribution of the rain throughout the rainy season determine the type of crop, the crop variety and the planting date. These are the key factors in the annual farming strategy of the local farmers.

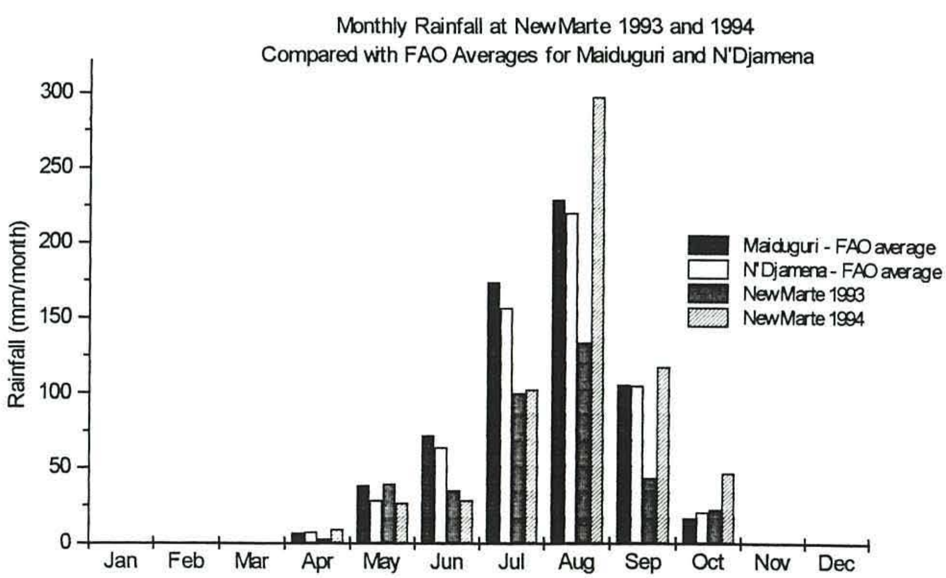


Figure 1.5 Monthly mean rainfall at New Marte, N'djamena and Maiduguri

The distribution of rainfall throughout the year is similar in all locations, with a period where no precipitation occurs between the months of November and March inclusive. A comparison of values plotted in figure 1.5 reveals that the New Marte site received above average rainfall in the period of August through to October 1994, whilst the remainder of the rainy period was mostly below average in this year. When the total values for each year are considered it is immediately evident that New Marte experienced only a relatively small amount of rainfall in 1993 (Figure 1.6).

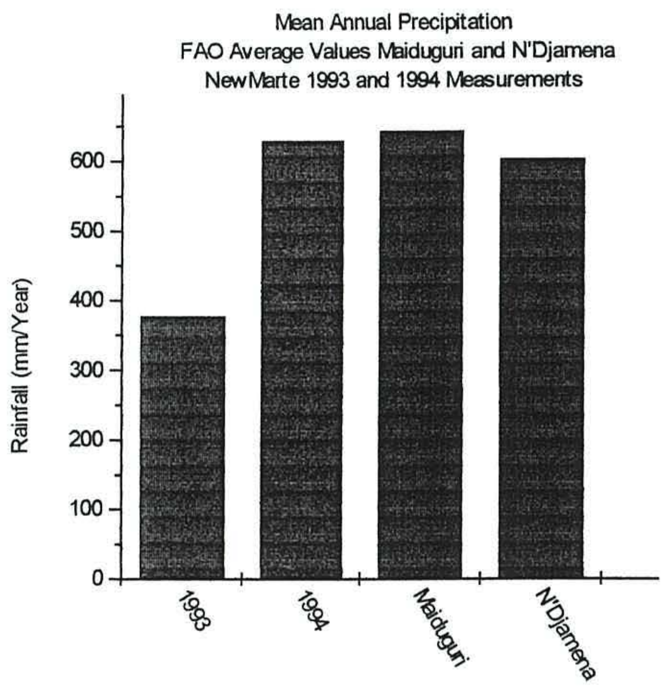
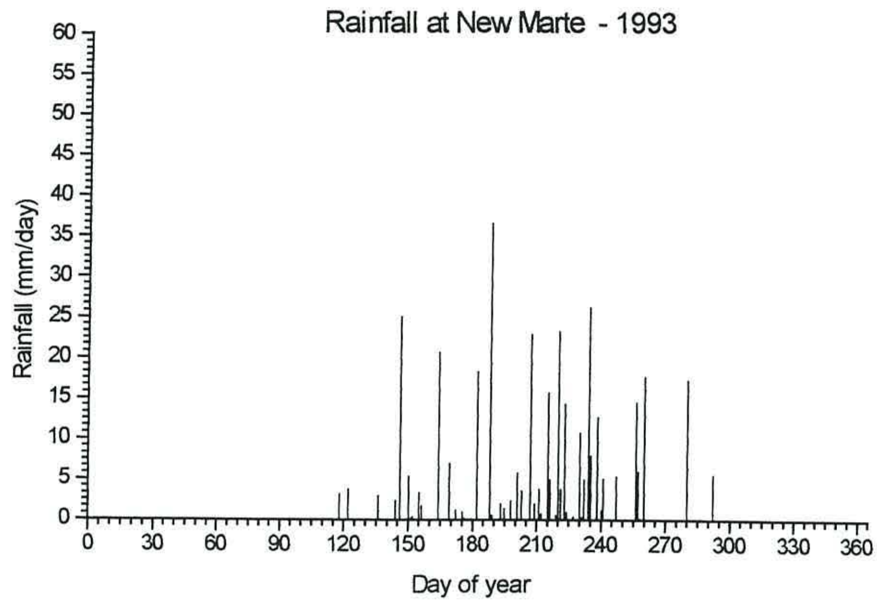
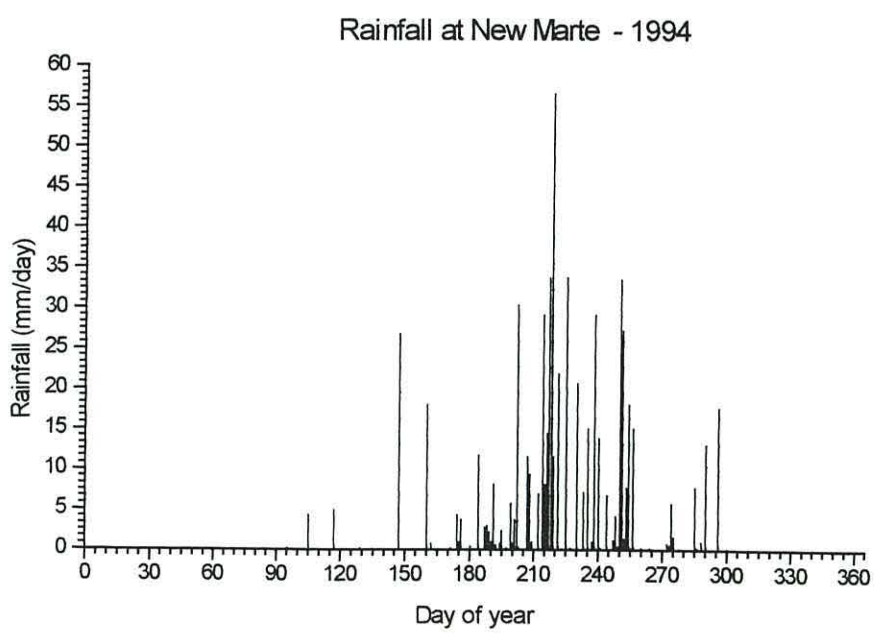


Figure 1.6 Annual mean precipitation at New Marte N'djamena and Maiduguri

The below-average annual rainfall of 1993 is most notable in the low values for June, July, August and September (see figure 1.5). In this year the rainfall was still spread over the same time period of the year as that of the average values but with lower quantities in these four key months. This would seem to reinforce local opinion that the distribution of the rains throughout the year is becoming increasingly erratic. In 1992 across northern Nigeria, the NEAZDP development project recorded total rainfall values of 549 mm at Garin Alkali (12°50' N, 11°10' E), 236 mm at Maiduguri, and 320 mm at Kaska (*ca.* 13°20' N, 11°20' E) (Fellman, E.A. - personal communication). In the Sahel, Cross and Barker (1991) have reported that local people observe a deterioration of the water regime. This creates decision problems for the local farmers, particularly when a crop needs to be raised as seedlings before the onset of major rainfall events, and then transplanted, as is the case with sorghum. The daily total values show how erratic the distribution of rainfall can be (figures 1.7 & 1.8):





Figures 1.7 & 1.8 Total daily rainfall at New Marte 1993 and 1994

The most striking feature of figures 1.7 & 1.8 is the size of some of the individual rainfall events. These often contribute more than 50% of the monthly total in the lower rainfall months, emphasising the spasmodic and localised nature of rainfall events in this region. The measurement of the rainfall at New Marte is in common with all rainfall measurements; it is obtained from a single small rainguage at a specific location. In this instance a standard tipping-bucket device was used. Because the measurement of rainfall is made at a point source there is no accommodation in the measurement for rainfall falling elsewhere that is translocated by mass flow to the area of interest. It is therefore difficult to gain an impression of the total amount of water that any particular area receives. This does, however, emphasise the importance of controlling water movement, principally by the construction and management of bunds.

1.5.2 Temperature

The temperatures experienced in the region are relatively less important, in terms of crop production, than rainfall. Figures 1.9 and 1.10 show the mean monthly temperatures at Maiduguri and at N'djamena.

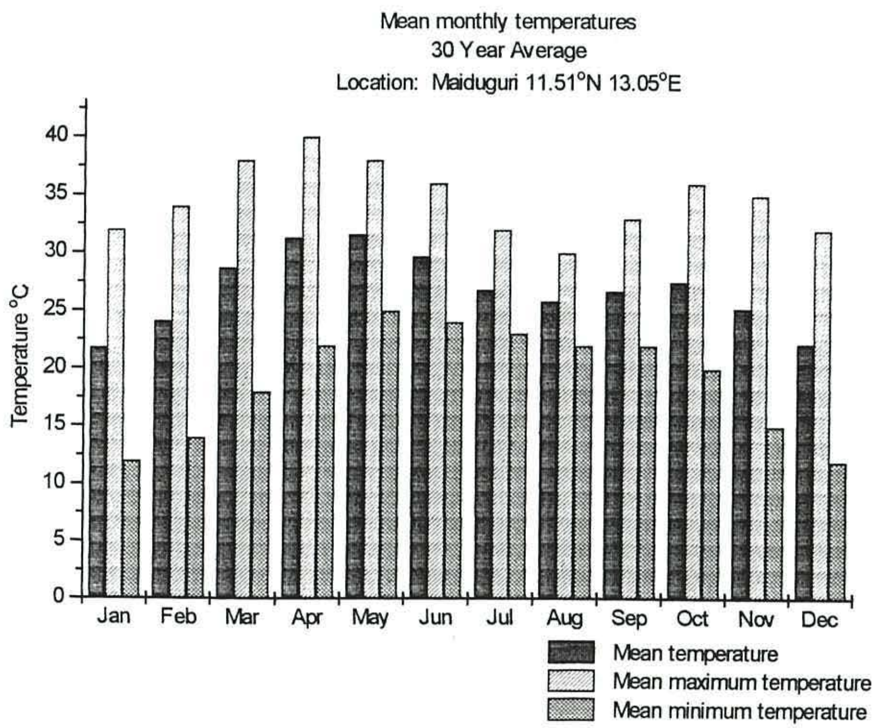


Figure 1.9 Mean monthly temperature for Maiduguri

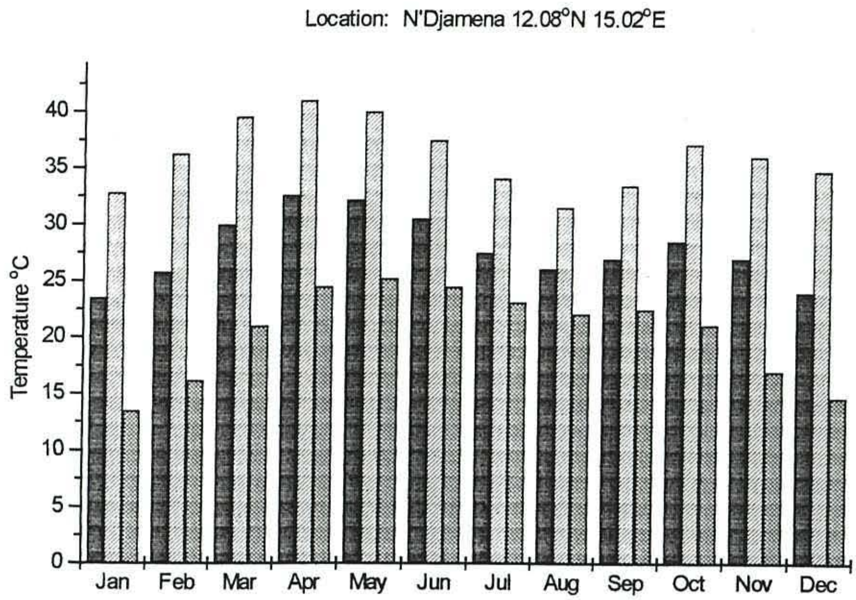
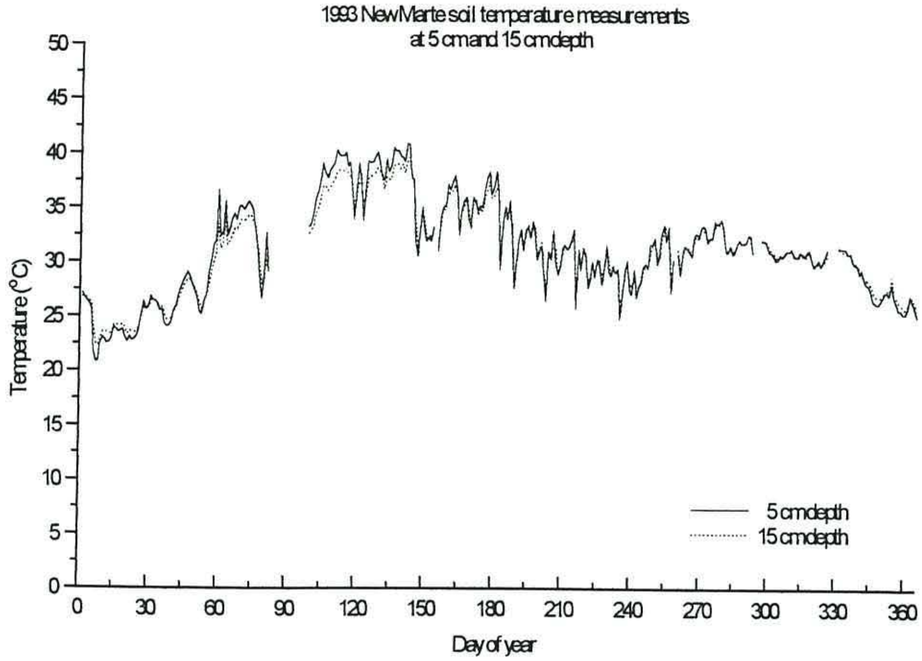


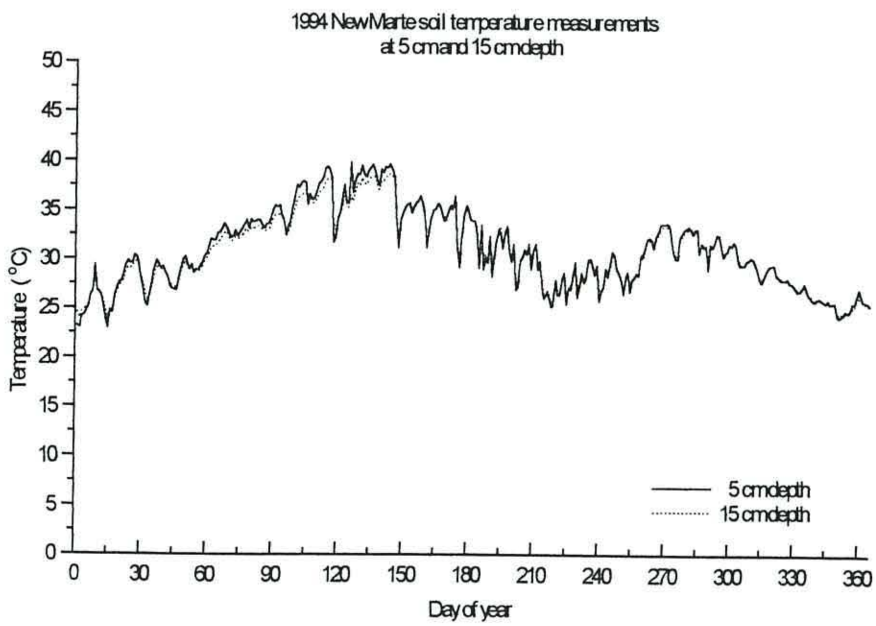
Figure 1.10 Mean monthly temperature N'djamena.

The influence of two factors contributing to the changes in temperature are reflected in these data. The high humidity and rainfall found in the rainy season of June to October are responsible for the slight lowering of the mean temperature relative to the months of April and May. Also noticeable is that the diurnal temperature range is much reduced during the rainy period. This is partly attributable to the slightly longer daylight hours but is mainly due to the influence of the high humidity. The air mass responsible for the rainy period is slightly cooler than the air mass found over the area during the dry season.

1.5.3 Soil Temperature

As part of a set of continuous measurements made at New Marte, soil temperature was recorded throughout 1993 and 1994. Recordings were made from two probes at depths of 5 cm and 15 cm. The probes were situated within the confines of the meteorological station at the New Marte field site, an area of disturbed sand-rich soils. The mean daily measurements are shown for each year in figures 1.11 and 1.12.



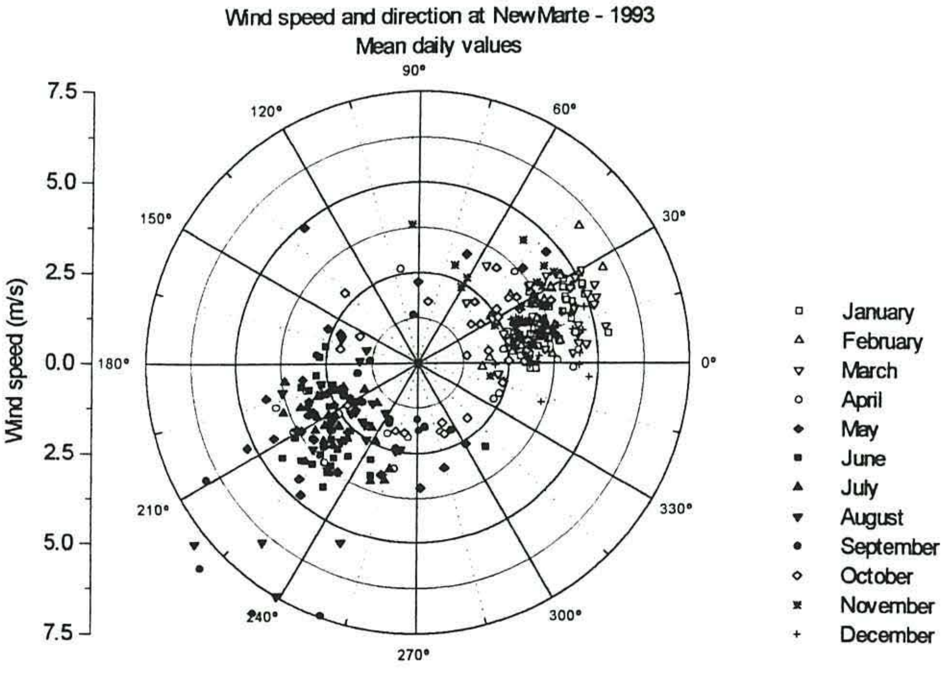


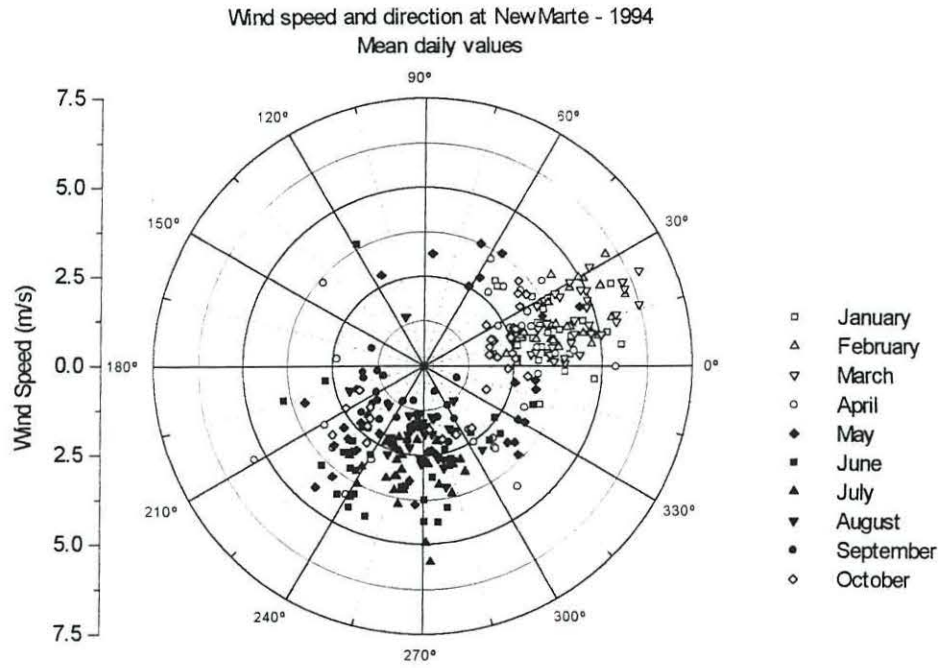
Figures 1.11 & 1.12 Soil temperature measurements at New Marte field site

When compared across the whole year these measurements appear to follow the trend of the regional above-ground air temperatures shown in figures 1.9 and 1.10. When the two depths are compared there is little difference between measurements. Despite the large difference in the rainfall between 1993 and 1994 (figure 1.6) and in its distribution (figures 1.7 and 1.8), the soil temperature measurements are very similar for both years, suggesting that the rainfall and standing water are not major factors in the measurements made at this specific location. The mean annual soil temperature at 15 cm (calculated using both years data) is 30.9 °C.

1.5.4 Wind Direction

The moist air mass of the rainy period is accompanied by SW winds but during the dry season the wind direction is predominantly from the NE. In order to show the switch in the wind direction from the rainy season to the dry season, two compass-rose plots have been constructed from the data obtained from a wind vane and an anemometer located at New Marte for 1993 and 1994 (Figures 1.13 & 1.14). The average FAO data that have been used as a comparison with the rainfall and the temperature measurements does not encompass wind direction or wind speed.





Figures 1.13 and 1.14 Wind speed and direction at New Marte 1993 and 1994

During the dry season, particularly the months of December to March, the NE wind causes large-scale movement of dust. This wind is known as the "Harmattan" and its influence is considerable. In the meteorological measurements this is clearly seen in the reduced temperatures experienced in the months of December to February where a significant amount of the incident radiation is occluded by the airborne dust. The large quantities of dust that the Harmattan carries, when deposited, form a significant component of soil parent material, particularly when long periods (kyr) of deposition are considered. Derived rates of dust deposition of up to 8.8 g cm^{-2} kyr^{-1} have been reported in measurements made in recent excavations at an oasis at Kajemarum (13.31°N, 11.03°E) (Street-Perrott *et al.*, in press). These values are in line with the range of values quoted by Møberg *et al.*, (1991) on measurements made in 1984/5 but exceed those of McTainsh (1984), whose directly measured values, taken in 1976 - 9, were in the range 3.2 g cm^{-2} kyr^{-1}.

1.5.5 Summary of climatic information

The New Marte area receives a mean annual precipitation below 650 mm, with the rainy season typically a period of three to four months of erratic rainfall. In common with the Sahel region the amount of precipitation has varied greatly in recent years but recent measurements taken at Maiduguri in the period 1987-1991 (Figure 1.6) indicate an overall trend towards drier conditions, compared to the FAO average figures taken over much longer periods.

There have been many different classifications of aridity, depending on the circumstance of the commissioning organisation or the specific interest of the author (Cooke *et al.*, 1993). A commonly used index is the UNESCO classification (Table 1.1) and using this classification, the area of the site is described as "semi-arid" (P/ETP=0.4). This assumes that the mean annual (Penman) potential evapotranspiration is <1300 mm. This classification covers much of Africa at this latitude (figure 1.15).

Table 1.1 - Delimitation of aridity zones

Zone	
Subhumid	0.50 < P/ETP < 0.75
Semi-arid	0.20 < P/ETP < 0.50
Arid	0.03 < P/ETP < 0.20
Hyper-arid	P/ETP < 0.03

Where P = annual precipitation
and ETP = mean annual potential evapotranspiration (based on Penman formula)

Whilst the quantity and timing of rainfall is a primary characteristic of the climatic regime found, there are other significant characteristics which may discriminate this site from other semi-arid areas. The diurnal temperature range and the relative humidity vary considerably between the two seasons. In the cool period of November through to March, particularly when the Harmattan is present, there is a high diurnal temperature variation; between this period and the rainy season there is a hot, dry period of March to mid-July where the diurnal temperature variation gradually diminishes until the rains come and the overall average temperature drops. Similarly after the rainy season, in October, the daytime temperatures and the diurnal range both increase. This period is the main growing period of the crops planted such that they grow on the residual moisture in the soil. These conditions will, as in the rest of the Sahel, favour plants that use a C_4 metabolic pathway rather than those using a C_3 pathway, since the former are able to utilize the high light intensities because they are photosynthetically more efficient. Sorghum, the experimental intercrop planted at New Marte, is a plant that utilises the C_4 metabolic pathway.

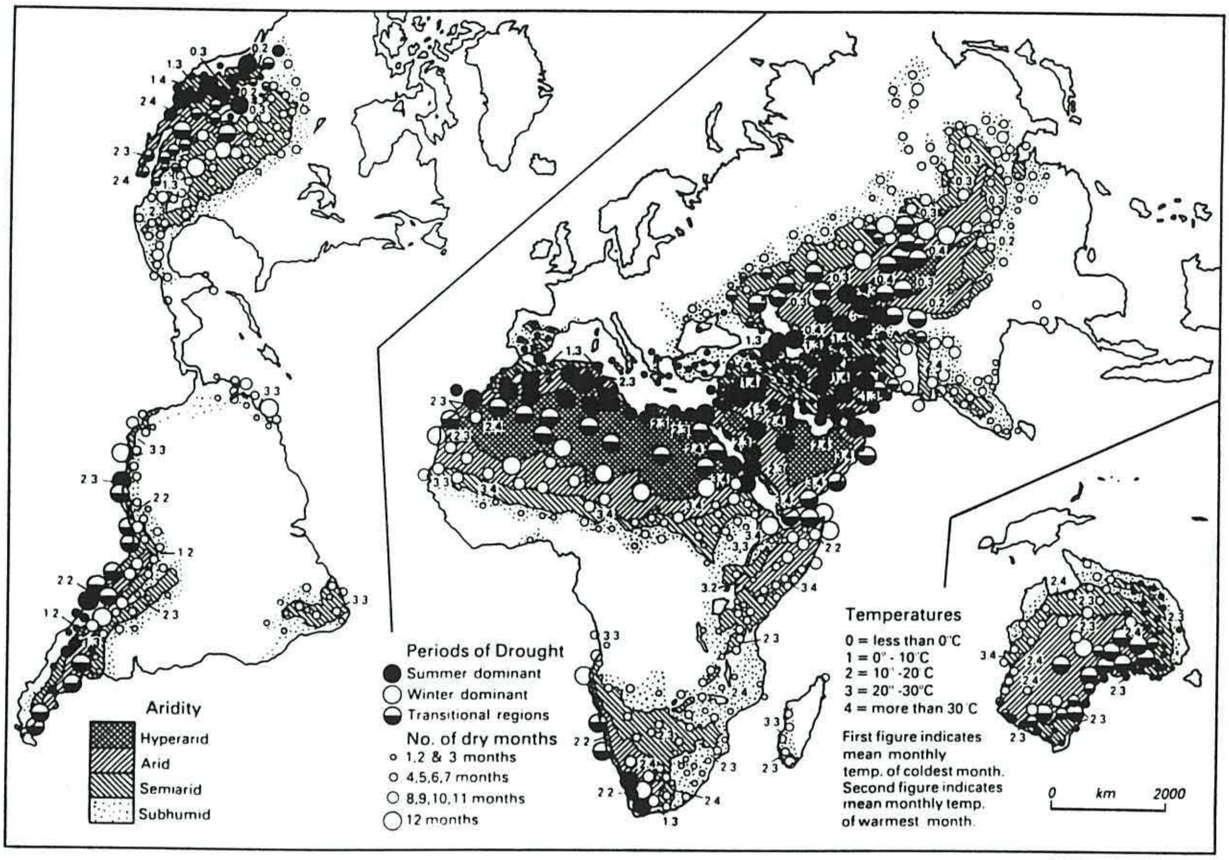


Figure 1.15 - UNESCO World Map of aridity

From the climatic information that is available it is possible to derive a climatic classification, giving an indication of the type of soils that are likely to be found. The most common climatic classification used in relation to soils is that used in the USDA Soil Taxonomy (Soil Survey Staff, 1975; *ibid.*, 1994). Whilst there is no long term information on soil temperatures at the depths required in Soil Taxonomy, we can estimate that the soil temperature regime is classified as *hyperthermic,* which is defined as having a mean annual soil temperature of greater than 22 °C and a seasonal (winter to summer) range of greater than 5 °C. Using this classification of the soil temperature, and the fact that there is a continuous period of longer than 90 days without rainfall, the soil moisture regime is classified as *Ustic,* (derived from Latin: *ustus* meaning burnt). The *Ust-* term is used as prefix in naming soils at the Suborder (*e.g.* Ustoll) and Great-group (*e.g.* Ustifluvent) levels of classification.

1.6 GEOLOGY AND GEOMORPHOLOGY

1.6.1 Geology of Chad Basin

The geological history of the Chad Basin (*ca.* 15000 km^2) is linked to that of the neighbouring Iullmedden basin (*ca.* 14000 km^2) which extends over the western reaches of Northern Nigeria and across Niger. The site at New Marte lies in the southern part of the Chad Basin. The area encompassing both of these large basins has been subject to several geological surveys. In the Chad Basin these have latterly been stimulated by the occurrence of oil in the western extremes at locations within Niger (Wright, 1985). The geological boundary between the two basins is a line between the Aïr and Zinder massifs - the so-called Damergou gap. Both basins have themselves spawned smaller basin features and both in turn appear to be part of a larger basin or depression from the Mesozoic era. The solid geology of the area is shown in figure 1.16. Focussing upon the Chad Basin, these surveys (*e.g.* Petters, 1981) reveal a basin of Cretaceous shales and sandstones of both marine and continental origin overlain by continental Paleocene deposits. The Cretaceous shales are exposed at the western extreme of the Chad Basin near the Damergou gap.

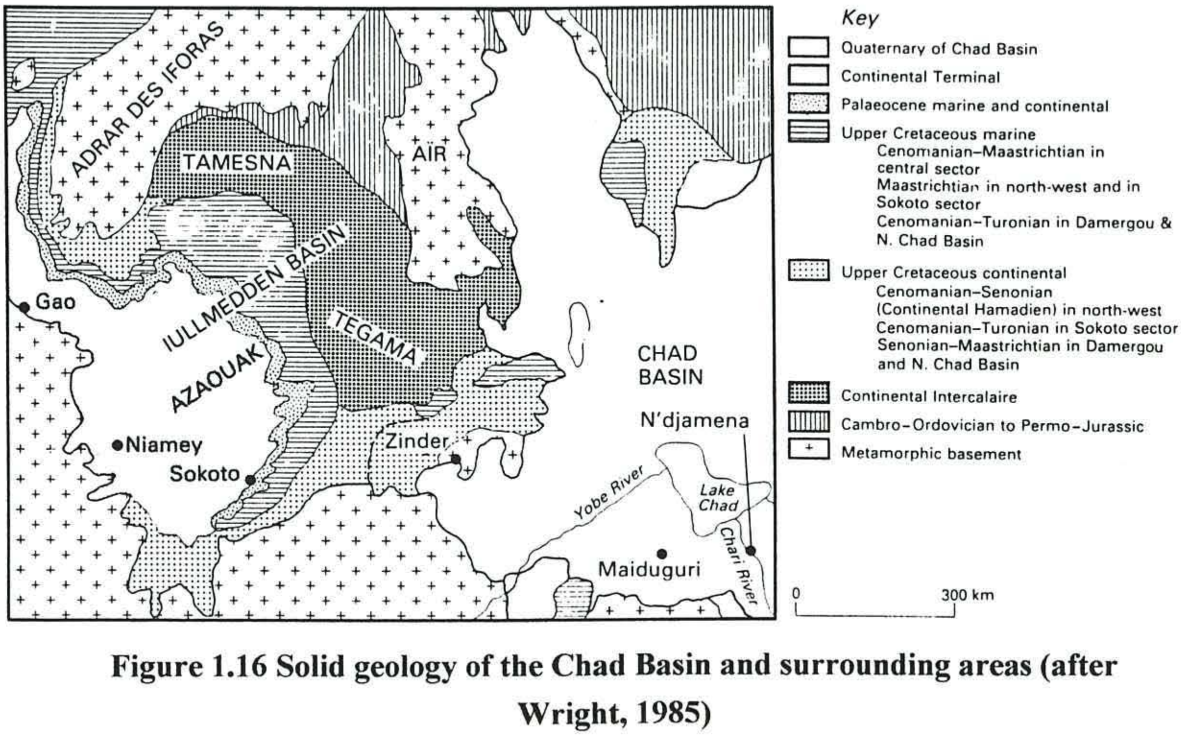
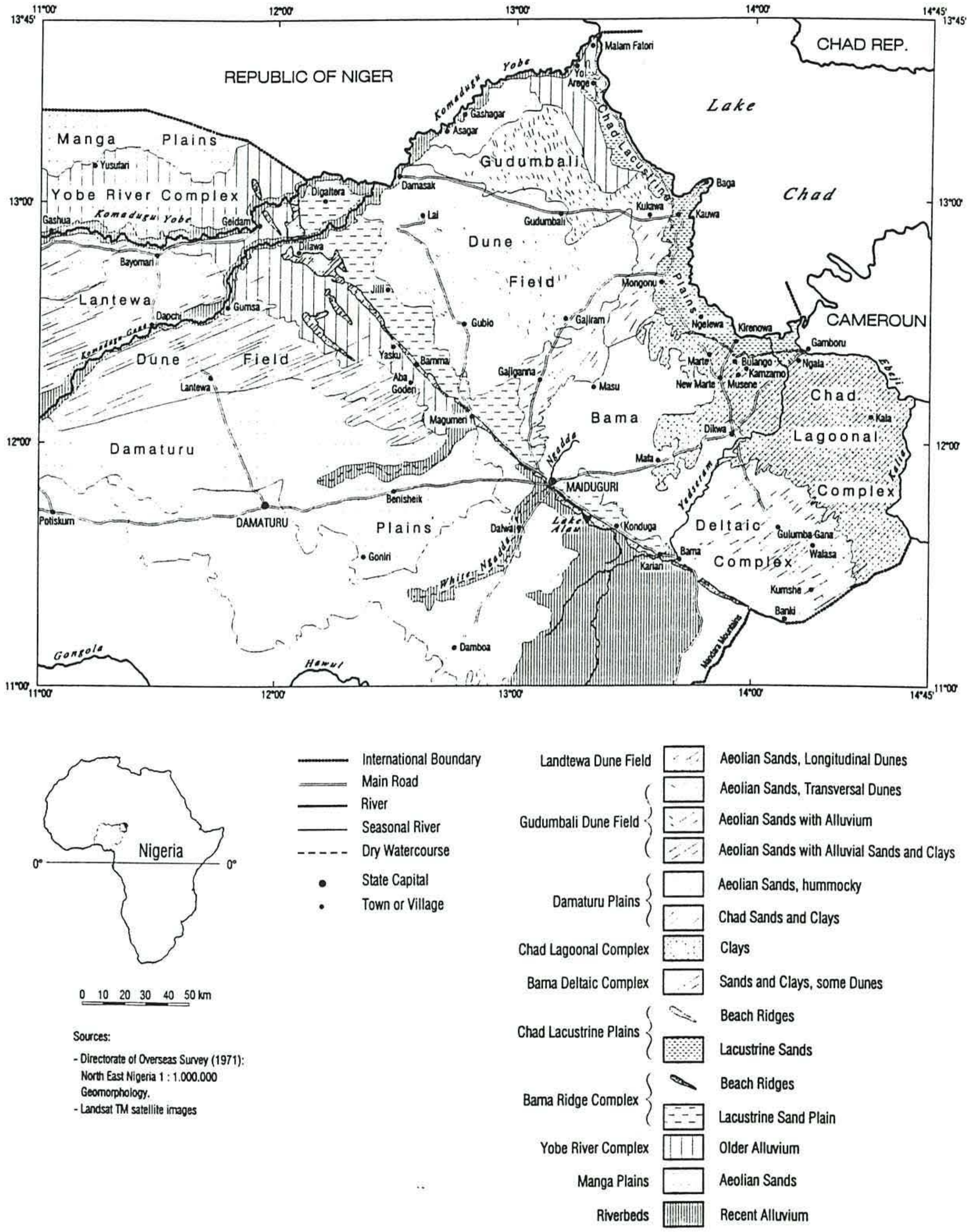


Figure 1.16 Solid geology of the Chad Basin and surrounding areas (after Wright, 1985)

Younger Tertiary deposits consist of both fluvial and lacustrine sands and clays. This trend has continued into and throughout the Quaternary period, dune fields produced by aeolian deposition and beach ridges developing where lacustrine clays have not breached or inundated the underlying sands. Figure 1.17 shows the superficial geological and geomorphological features.

Figure 1.17 Superficial geology and geomorphological features of Chad Basin (after Aitchison *et al.*, 1972 with LANDSAT additions by H. Thiemeyer)



1.6.2 Geomorphology of region

The description by Grove (1958) of the *ancient erg of Hausaland*, whilst outlining the extent of the dune fields, for the first time also denoted several dune features as possible former margins of Lake Chad. Of particular note is the prominent sand ridge known as the "*Bama Ridge*" (Carroll, 1974), occasionally denoted in Niger as "*le cordon de Tal*" (Bocquier, 1973) and in Cameroon as "*le cordon sableux sud*" (Pias, 1962). Since Grove noted this ridge as a possible lake margin (Grove, 1958; Grove, 1959), this theme has been expanded by many authors (*e.g.* Pias, 1970) and there is general agreement that Lake Chad experienced a series of recession and expansion events in the Holocene, although the magnitude and timing of these fluctuations is still disputed.

The history of Lake Chad has been studied using stratigraphic and hydrological methods. These have indicated that the most recent major fluctuations have occurred during the last fifty thousand years, when it is postulated (Durand, 1982) that the lake had reached maxima at 38,000; 22,000 and at 8,000 to 12,000 years B.P.. This portrait of a lake successively expanding and contracting was, until recently, subject to debate (Servant, 1983; Durand *et al.*, 1984), since the origin of the beach ridges remained unproven. The Bama Ridge is commonly assumed to be the outermost margin of Lake Chad at its largest maximum. However the recent discovery and analysis of archaeological remains, principally charcoal and potsherds, from settlements at Konduga on the Bama Ridge, has allowed ^{14}C dating to take place (Thiemeyer, 1992). This places a date of 6000 years B.P. on the artefacts, suggesting that this is the last lake maximum described in the paleo-lake hypothesis of Durand.

The superficial geology (Figure 1.17) of the southern and western margins of Lake Chad presents a distinct contrast between an area of undulating sand dunes to the west and lacustrine clay deposits in the south. It is conjectured that this distinction may be due to a fault or other disruption of the underlying shales rendering the western part more susceptible to aeolian deposition.

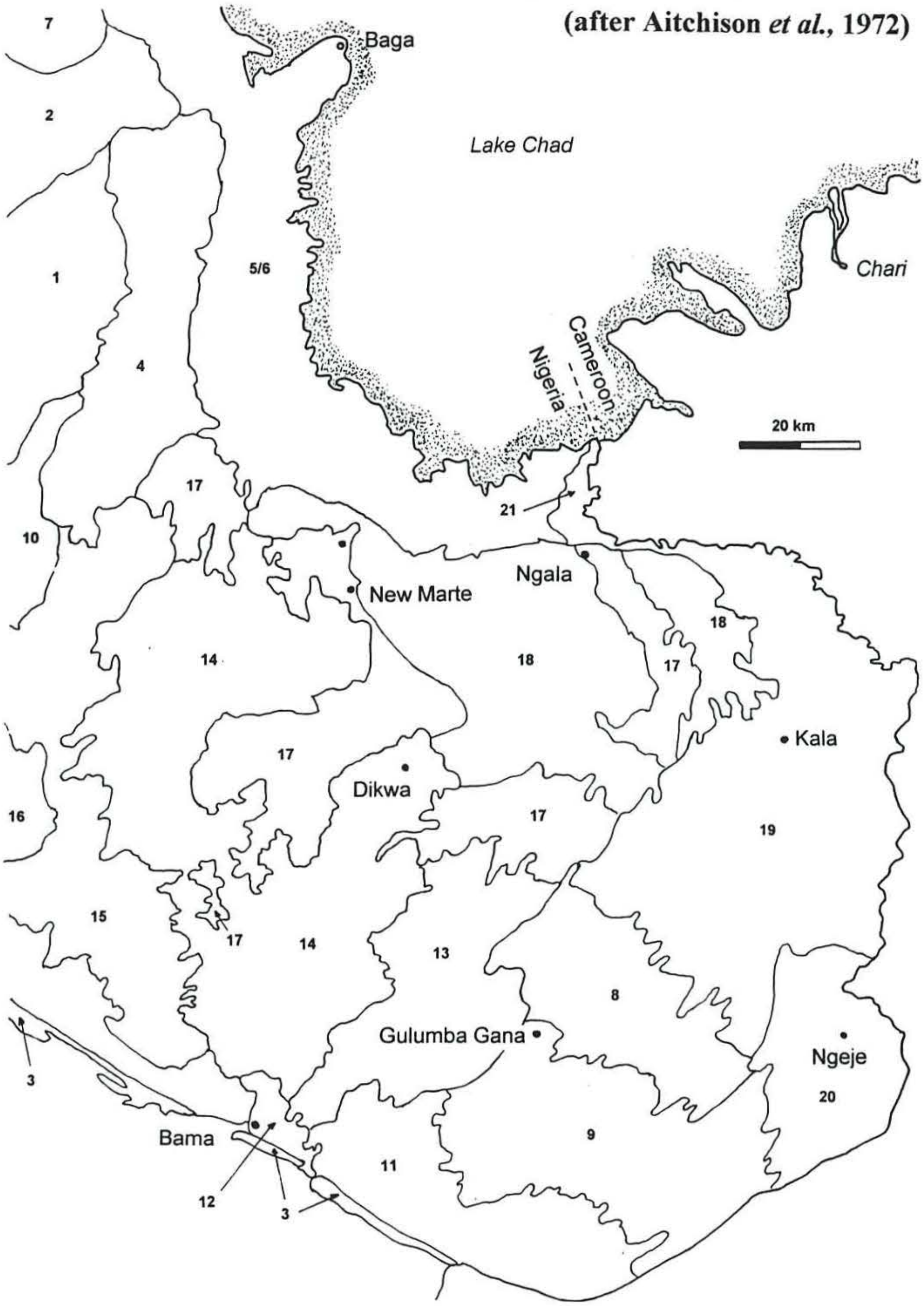
The topographic relief in the southern parts of Chad basin is characterized by the vast areas of lacustrine deposits which, whilst varying in depth, show little surface fluctuation. A difference in altitude of 40 m exists from the current 1992 lake level to the Bama ridge (Thiemeyer, 1992a); the distance between these two points is in excess of 120 km with no pronounced relief. This superficially featureless lacustrine plain is, however, penetrated by the deltas of the Yedseram, Alo and many smaller rivers. These extend towards Lake Chad from the positions where they breach the Bama Ridge. Other older, relict, deltaic systems have also been recorded from aerial survey (Pullan, 1964).

1.6.3 Soil Parent material

Where lacustrine clays have been deposited and subsequently exposed as Lake Chad has receded, there has been a development of distinctive dark-grey clay-rich soils classified by Tuley (1972) as *vertisols* and described by Beavington (1978) as *cracking clay* soils. The ultimate origin of the clay material would appear, from the current drainage pattern of the area, to be from the basaltic igneous rocks, found in such areas as the Mandara mountain range, to the south and east of this region (see figure 1.16).

The Chad Basin forms the largest expanse of recently exposed lacustrine deposits world-wide (1.4 million ha). The soils forming on such material, predominantly vertisols and what may be termed proto-vertisols, account for an area of 43 million ha (IRRI, 1980) in sub-Saharan Africa. This represents approximately 40% of the land surface of this region. World-wide the land area classified as vertisols extends to some 300 million ha (IBSRAM,1987). The location of this experimental site at New Marte places it within an area classified by FAO-UNESCO (1977) as a "fine textured chromic vertisol". The vertisols of this area extend over a land system termed the Marte Clay Plains (Aitchison *et al.*, 1972 - Land systems map 6a); part of this map is reproduced in figure 1.18. Pullan (1969) described the 'Firki' field system around Marte and Dikwa, and the physical and mineralogical properties of these latter soils have been considered during the construction of roads in the region (Ackroyd and Husain, 1986). The site at New Marte lies to the west of the Firki Plains and is readily differentiated from them, since it has larger accumulations of overlying aeolian sand.

Figure 1.18 Land system classification (after Aitchison *et al.*, 1972)



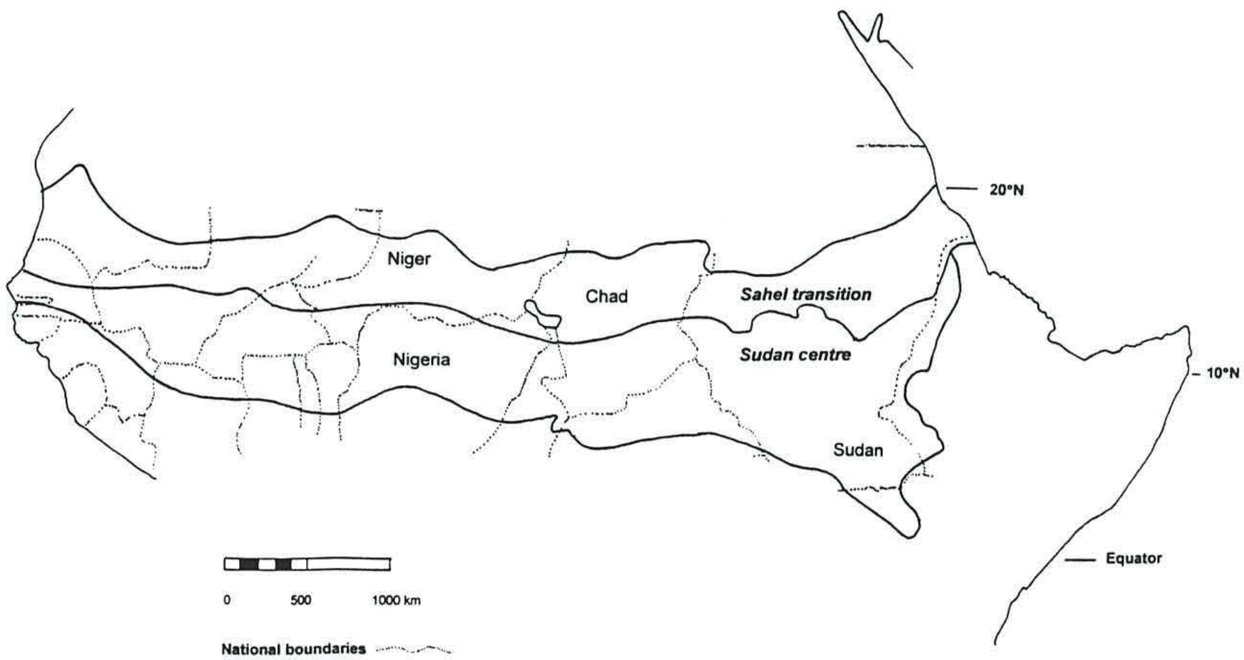
Land Region	Land system	Key
North west transverse dune field		
	Gudumbali dune field	1
	Banawa dune field	2
	Bama ridge	3
	Kukawa dune field	4
Lacustrine sands		
	Mongonu plain	5
	Lake Chad edge	6
Yobe alluvial complex		
	Yo alluvial plain	7
Chad longitudinal dune field		
	Musgowa dune field	8
	Mabaraka dune field	9
	Zumfur plain	10
Bama fluvial/delataic complex		
	Yabiri delta	11
	Mastari fans	12
	Bama plain	13
	Yedseram delta	14
	Bida plain	15
	Alo delta	16
Chad lagoonal complex		
	Marte plains	17
	Ngala plains	18
	Kala plains	19
	Ngeje plains	20
	El Bied flood plain	21

1.7 VEGETATION AND LAND USE

1.7.1 Vegetation classification

The area of study is positioned at the northern limit of the Sudanian Centre vegetation zone, immediately south of the extensive Sahel transition zone (Figure 1.19; White, 1983). No distinct vegetational differences occur latitudinally due to the lack of relief and similar climate conditions across the region. The vegetation pattern of the region is therefore characterised as a mosaic of grassland and wooded areas of varying density. *Acacia* is the principal tree species in these wooded areas.

Figure 1.19 Map of vegetation classification (adapted from White, 1983)



1.7.2 Farming Systems

The systems of land-use and farming on these areas has been described by Braukämper *et al.*, (1993). The traditional rotation pattern of the region is a long bush fallow alternating with cropping, principally of sorghum and of millet on freer draining soils. An essential part of many of the farming systems employed is the use of bunds. These are raised linear mounds of earth used as a barrage against overland water movement (Plate 1.1). The bunding system allows for the management of rainfall inputs depending upon the amount of rain in the rainy season. In addition to the use of bunds, the amount of water entering the soil and available for use by plants will vary according to the nature and management of the soil.

The current agricultural use of land in this region is dominated by the cultivation of Masakwa. Masakwa is the local landrace of *Sorghum bicolor* and its key characteristic is that it grows on the residual moisture after the rainy season. The area under masakwa cultivation extends, in Nigeria, approximately from 11°45'N to 12°30'N and from 13°30'E to 14°30'E. Masakwa cultivation appears limited to the lacustrine clay plains of North East Nigeria. The practice of growing sorghum on residual moisture has not been adopted in the Hadejia - Nguru wetlands area (12°45'N 10°15'E), although trials were started in 1994 (Plate 1.2) at Gorgoram (12°45'N 10°45'E) a seasonally flooded riparian wetland.

Where the field conditions in the lacustrine plain do not permit the successful planting of Masakwa, other crops may be grown: millet in drier areas and rice in ponded areas. The land system survey of Tuley (1972), whilst commenting on the range of crops does not indicate in detail the distribution of such cropping. In the less populated areas of the region, extensive stands of *Acacia sp.* are occasionally found. This lies is in contrast to 1914, when Foster reported that such *Acacia* stands were a common feature of the landscape.

Plate 1.1 Bunds created in fields near the village of New Marte
Plate 1.2 Masakwa being planted in the floodplain of the Bunga river near Gorgoram, Yobe State, Nigeria.

1.8 NEW MARTE EXPERIMENTATION

1.8.1 History of experimentation undertaken at New Marte field site 1987 - 1991

The field site at New Marte was established in order to study the establishment of five tree species as multipurpose agroforestry tree species. These were selected on the basis of being available locally as either indigenous species or as species that have been adopted by some farmers in the region and become naturalised. The most prominent indigenous tree species in the area are the legumes *Acacia nilotica, A. senegal and A.seyal* and the non-leguminous *Balanites aegyptiaca* and *Ziziphus sp.* The first four of these species and a fast growing naturalised legume, *Prosopis juliflora,* have been used in the agroforestry experimentation. The vegetation, found at the site location when the experiment was started in 1987 and presently (1995) found in the surrounding area is sparse with only relict trees and much bare ground in the dry season (see plates 1.3 and 1.4). Despite this, the area is gazetted as a forest reserve.

In order to compare these species and assess their initial growth and performance whilst being surrounded with an intercrop of sorghum (*Sorghum bicolor*), a large scale experiment was initiated. The site covers an area of 30 ha and is divided into four blocks. Each block in turn is divided into year strips which in turn are divided into two halves: one half intercropped the other not. Each of these year/intercrop divisions is divided into twelve 25 m x 25 m plots (figure 1.20). This design is described as a randomised split-split plot with double replication at the lowest (split-split plot) level. Since the tree planting took place over five years the design allows for the comparison of different climatic factors and, by inference, the relative performance of the different tree species to these factors.

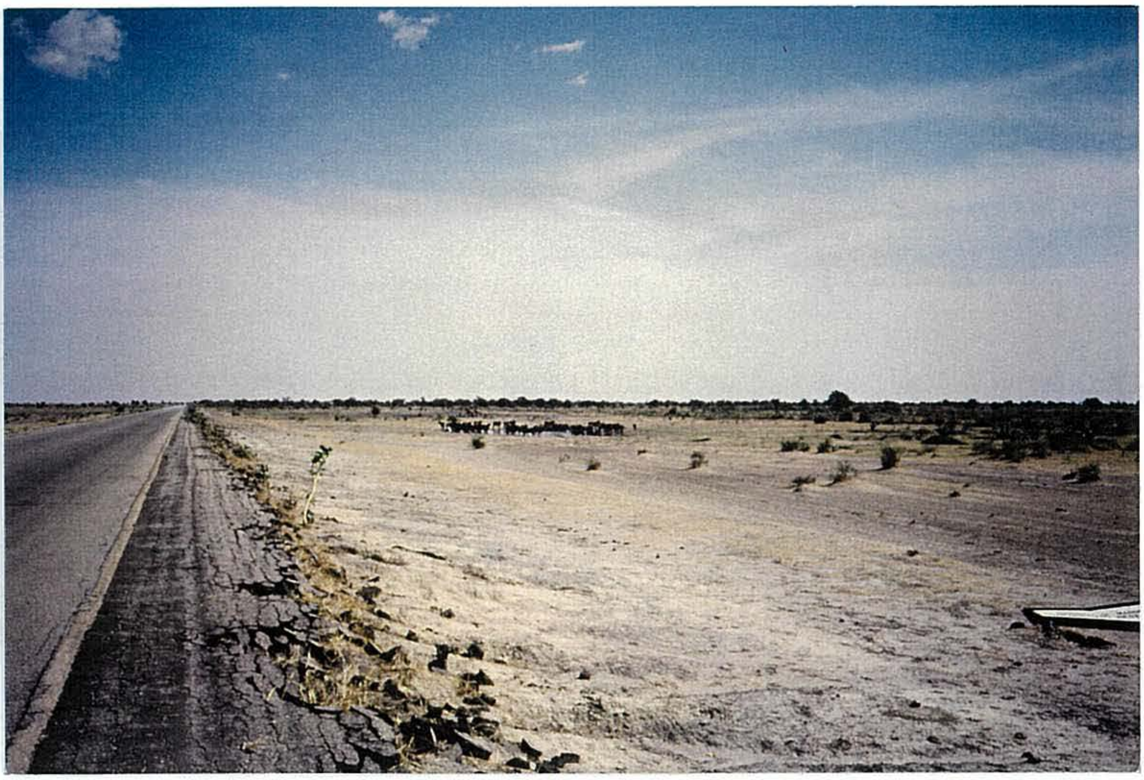


Plate 1.3 Area around New Marte field site

Plate 1.4 The New Marte field site - showing sorghum being harvested

Figure 1.20 Map of experimental layout at New Marte field site

BLOCK 4 | BLOCK 3

Year	89		87		88		90		91		88		90		91		89		87	
	6	4	3	5	4	6	6	3	4	5	3	3	2	6	1	5	2	1	3	5
	2	3	6	4	1	2	5	4	2	6	1	2	2	5	2	2	6	5	6	4
	1	2	2	1	6	3	2	3	5	6	2	5	1	6	3	3	4	2	2	1
	4	1	4	2	2	1	4	1	1	3	6	6	3	1	6	4	5	4	4	2
	5	6	1	3	3	4	2	1	3	2	4	1	5	4	4	5	3	3	1	3
	5	3	6	5	5	5	6	5	1	4	5	4	3	4	6	1	6	1	6	5
	3	4	3	2	3	1	6	6	6	2	5	6	1	3	6	6	2	6	3	2
	4	2	6	4	6	4	5	5	3	2	5	4	6	4	5	4	4	4	6	4
	6	2	6	5	5	5	2	3	6	5	4	6	4	6	3	1	3	2	6	5
	3	6	3	4	6	2	1	2	4	1	3	1	3	2	4	3	3	1	3	4
	5	1	5	1	3	4	4	1	4	5	1	2	1	5	2	2	5	5	5	1
	5	1	1	2	2	1	3	4	1	3	3	2	2	5	1	5	1	6	1	2

	6	6	1	2	4	4	3	2	6	4	2	6	2	3	6	6	6	5	3	4
	4	2	1	2	6	6	2	6	3	4	1	2	6	1	4	4	5	3	5	2
	4	1	3	4	1	1	5	6	5	2	5	4	2	4	5	3	4	2	1	4
	2	3	6	5	3	2	1	3	1	6	6	3	5	3	1	3	3	1	1	3
	1	3	4	3	3	5	5	4	2	1	3	5	4	6	5	1	2	6	6	6
	5	5	5	6	5	2	1	2	5	3	4	1	1	5	2	2	1	4	2	5
	3	3	6	4	5	5	4	1	6	1	2	3	5	4	3	6	6	2	1	3
	4	2	5	5	2	6	4	2	2	5	3	1	2	3	6	5	3	4	6	2
	5	5	2	3	6	1	3	6	1	6	6	5	4	6	1	4	2	1	3	2
	6	1	1	2	3	2	1	6	4	5	4	1	5	1	4	1	3	1	5	6
	6	4	4	6	3	1	2	5	4	2	5	6	3	1	5	2	5	4	4	1
	1	2	3	1	4	4	5	3	3	3	4	2	2	6	2	3	6	5	5	4
Year	91		87		88		90		89		88		90		89		91		87	

BLOCK 2 | BLOCK 1

Key to plots

1 Control plot (no trees)
2 *Acacia nilotica*
3 *Acacia seyal*
4 *Acacia senegal*
5 *Balanites aegyptiaca*
6 *Prosopis juliflora*

(shaded) Plots intercropped with sorghum

Other information

Size of plots = 25 m x 25 m
No. of trees per plot = 25
No. of plots per *sp* per year = 16
No. of trees per *sp* per year = 400
Total no. of trees per year = 2,000
Total no. of trees planted = 10,000

BLOCK IV | BLOCK III

Year	89		87		88		90		91		88		90		91		89		87	
	457	433	409	385	361	337	313	289	265	241	217	193	169	145	121	97	73	49	25	1
	458	434	410	386	362	338	314	290	266	242	218	194	170	146	122	98	74	50	26	2
	459	435	411	387	363	339	315	291	267	243	219	195	171	147	123	99	75	51	27	3
	460	436	412	388	364	340	316	292	268	244	220	196	172	148	124	100	76	52	28	4
	461	437	413	389	365	341	317	293	269	245	221	197	173	149	125	101	77	53	29	5
	462	438	414	390	366	342	318	294	270	246	222	198	174	150	126	102	78	54	30	6
	463	439	415	391	367	343	319	295	271	247	223	199	175	151	127	103	79	55	31	7
	464	440	416	392	368	344	320	296	272	248	224	200	176	152	128	104	80	56	32	8
	465	441	417	393	369	345	321	297	273	249	225	201	177	153	129	105	81	57	33	9
	466	442	418	394	370	346	322	298	274	250	226	202	178	154	130	106	82	58	34	10
	467	443	419	395	371	347	323	299	275	251	227	203	179	155	131	107	83	59	35	11
	468	444	420	396	372	348	324	300	276	252	228	204	180	156	132	108	84	60	36	12
	469	445	421	397	373	349	325	301	277	253	229	205	181	157	133	109	85	61	37	13
	470	446	422	398	374	350	326	302	278	254	230	206	182	158	134	110	86	62	38	14
	471	447	423	399	375	351	327	303	279	255	231	207	183	159	135	111	87	63	39	15
	472	448	424	400	376	352	328	304	280	256	232	208	184	160	136	112	88	64	40	16
	473	449	425	401	377	353	329	305	281	257	233	209	185	161	137	113	89	65	41	17
	474	450	426	402	378	354	330	306	282	258	234	210	186	162	138	114	90	66	42	18
	475	451	427	403	379	355	331	307	283	259	235	211	187	163	139	115	91	67	43	19
	476	452	428	404	380	356	332	308	284	260	236	212	188	164	140	116	92	68	44	20
	477	453	429	405	381	357	333	309	285	261	237	213	189	165	141	117	93	69	45	21
	478	454	430	406	382	358	334	310	286	262	238	214	190	166	142	118	94	70	46	22
	479	455	431	407	383	359	335	311	287	263	239	215	191	167	143	119	95	71	47	23
	480	456	432	408	384	360	336	312	288	264	240	216	192	168	144	120	96	72	48	24
Year	89		87		88		90		91		88		90		91		89		87	

BLOCK II | BLOCK I

Figure 1.21 Plot numbering scheme at New Marte field site

The 480 plots in the experiment have been labelled sequentially from the NE corner to the SW corner (see figure 1.21). In each plot planted with trees, the tree spacing is at 5 m x 5 m. This combination of indigenous widely spaced trees contrasts with many of the agroforestry experiments conducted in the more humid parts of both West and East Africa, where great use has been made of hedgerow intercropping using fast-growing exotic tree species such as *Gliricidia sepium*, *Cassia siamea* and *Leucaena luecocephala*, all of which have been evaluated in ICRAF trials (Huxley *et al.*, 1989).

The design of the field experiment and the planting of the trees was undertaken by staff of the Forestry Department (latterly part of School of Agriculture and Forest Sciences), University of Wales, Bangor and the Department of Biological Sciences, University of Maiduguri, N.E. Nigeria. During this initial phase of experimentation a series of measurements was made on basic tree growth parameters. These include: tree survival, tree height, crown diameter, and the cross-sectional area of the tree stems. Additionally a set of soil samples was obtained from across the field site. The analysis of these samples forms the basis of the work presented in Chapter 4. The tree-growth results obtained in the fourth and fifth years of the experiment (1991/2) were used as a basis for developing the process-based research programme (1992 to 1995) that followed the initial phase of experimentation. The work on the experimental site presented in this thesis was undertaken in the period 1992 - 1996.

1.9 PLAN OF THESIS

This introduction has outlined the underlying themes and rationale for the work undertaken and described in this thesis. Firstly, the underlying contrast between the soil processes at the New Marte experimental site and those of the soils in the southern Lake Chad region in North East Nigeria is highlighted. The sequence in which the work is presented is such that the detailed discussions of methods and results from New Marte follow the necessarily more general measurements from sites across the region. Secondly, the influence of soil processes is placed within a broader context of agroforestry and land use, with conclusions drawn relating to these issues and suggestions for refining the experimentation. Table 1.2 lists the chapter titles and gives a brief summary of their contents.

Table 1.2 Chapter titles and summary of contents

Chapter		Summary
1	Introduction	States the aims and rationale of the thesis and provides a historical and geo-sociological introduction to the region of study.
2	Lacustrine derived soils of the Chad Basin: (A) Sampling	A review of previous soil surveys leads to the selection of field sites for this study. These sites are then described and characterised.
3	Lacustrine derived soils of the Chad Basin: (B) Laboratory description	Laboratory description of soils from regional profiles
4	The soils of New Marte experimental site	Description of chemical and physical measurements characterising the New Marte field site
5	Plot level examination of New Marte soils	Detailed plot level measurements of the New Marte field site
6	Soil structural characteristics	Pore analysis and other structural measurements of soils at New Marte in the context of the agroforestry experimentation
7	Direct measurement of infiltration at New Marte	Measurement of infiltration at the New Marte site and comparison with soil structural parameters
8	Effect of agroforestry tree planting on organic matter and nutrient inputs to the soil at New Marte	Inputs to the soil are quantified and discussed in relation to agroforestry tree planting and growth. A model simulation of tree influences on the soil is also described.
9	Discussion and conclusions	
	Appendices	

2 LACUSTRINE DERIVED SOILS OF THE CHAD BASIN: (A) SAMPLING AND DESCRIPTION

2.1 INTRODUCTION

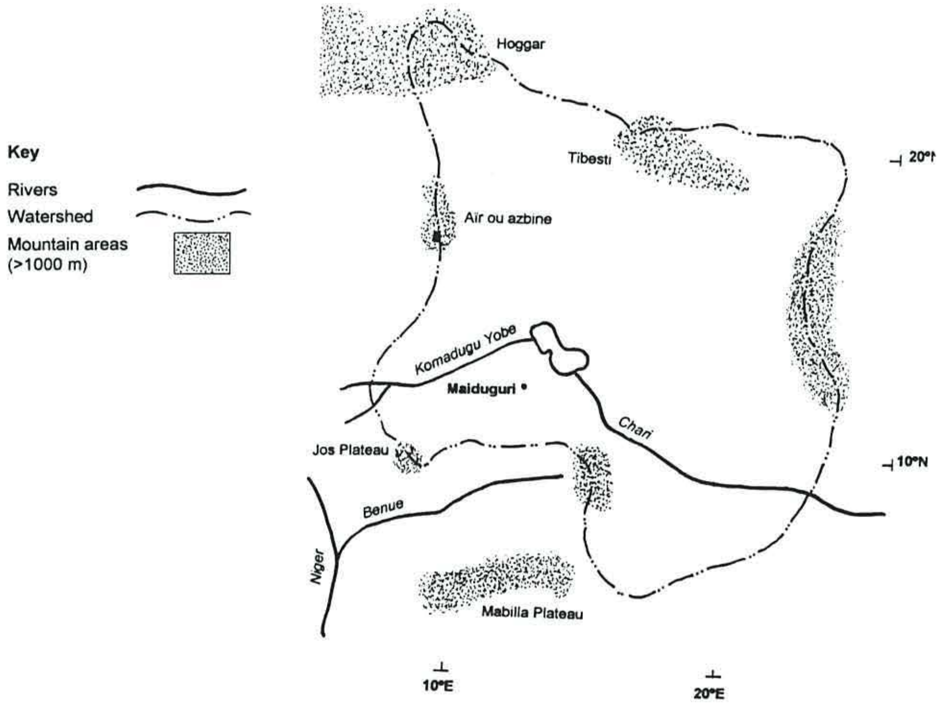
This chapter describes the characteristics of the soils that have developed in the Chad Basin and discusses the major influences on the pedogenesis of the soils found. The basis for selecting four positions to sample soil profiles is described in detail. These profiles were chosen to form both a topo- and a chronosequence. The information gathered relating to the soil chronosequence allows for predictions as to where soil development is coming-from and going-to for soils in the area. This information will be used later in discussions of the possible effects of tree planting on soils. The laboratory analyses of samples taken from these profiles are described in Chapter 3.

2.1.1 Lake Chad

Lake Chad is unique amongst the large lakes found in Africa, since it is at the centre of an extensive drainage basin but has no surface outflow and only relatively very small below-ground drainage towards the Bodele depression in Chad. The geomorphology of this drainage basin is described as "centripetal" using Gregory and Walling's (1973) terminology. The major rivers supplying the lake are the Chari and the Komadugu Yobe (see Figure 2.1). These rivers have both been extensively exploited by the creation of major up-stream dams (Maga dam on the Chari; Tiga and Challawa dams on the Komadugu Yobe tributaries) for water supply to urban areas, hydro-electric power generation, and for irrigation. In the case of the Komadugu Yobe, there is now little water flow evident for much of the year through Yo (Nigeria) and Bosso (Niger), where the river reaches Lake Chad. Additionally, there has been much greater exploitation of groundwater through boreholes and wells in recent years. This appears to be unsustainable, since many boreholes which fountained when installed in the late 1960's now require pumping. The overall result of this increased groundwater abstraction, and the systematic damming of rivers, including small rivers such as the Yedseram and Alo in Borno, Nigeria, is a diminution of Lake Chad. This diminution of the lake has allowed agricultural exploitation of the newly exposed land surrounding the open water of the reduced lake. For the local people this agricultural production helps to offset the effects of the loss of fishing (Sarch and Madakan, 1995). When an economic value is placed upon these products, it is possible that the agricultural output is greater than that that fishing produced (Sarch, 1995).

The increased agricultural use of land around the lake increases the need for the study of these soils. The exploitation of water has reduced the levels of Lake Chad such that its surface area has been reduced by approximately one-third in the last 30 years. Whilst there have been two severe drought periods in this period (Mortimore, 1989) and there is evidence of longer-term climatic changes influencing Sahelian lake levels (Street-Perrott, *et al.*, 1989) there is no doubt that damming and groundwater abstraction (Adams, 1992) are two major causes of the lake's diminution.

Figure 2.1 Surface drainage into Lake Chad (topographic information after Defense Mapping Agency Aerospace Center, 1982)



Despite the decrease in river water supplying Lake Chad, prolonged high evaporation rates, and the lack of an outflow from the lake, the salinity of the water is relatively low (*ca.* 0.40 g dm^{-3} dissolved salts), compared with "average" river water (0.12 g dm^{-3}) and sea water (35 g dm^{-3}); the water is also of the same ($Ca/Mg/Na/HCO_3$) type associated with river waters (Carmouze & Pedro, 1977; quoted by Wright, 1985). However there is an observed trend in water salinity increasing from the south to the north of the lake. This is also evident from the surface deposition of calcite and trona on the north and north-east shores (Wright, 1985). Various factors may explain the relatively low salinity, including the deposition of calcite, but the two main mechanisms for moderating salinity are through infiltration into below-ground aquifers and from the precipitation of smectitic clay minerals. In addition to these cations, the precipitation of smectitic clay minerals requires conditions with relatively high pH and high Al/Si ratio. Measurements made by du Preez and Barber (1965) on a range of Chad Basin groundwater samples are consistent with these required conditions.

The social and political aspects of the exploitation of water have been discussed in both general (*e.g.* Goudie, 1993) and specific (Adams, 1992) geographical contexts. Adams (1992) discusses the social implications of the diminution of Lake Chad with specific reference to the large scale irrigation projects that were constructed in Nigeria, drawing their water from Lake Chad, during the late 1970's – early 1980's period. The planning and construction of these projects provided a large amount of survey work on geological and hydrogeological conditions in the Lake Chad region. Soils were not considered with the same detail at this regional level. Therefore the main sources of information on soil classification in the Nigerian section of the Chad Basin are from the Colonial period (1903 - 1960) and from those commissioned in the immediate post-independence period (1960 - 1970).

2.2 PREVIOUS SOIL AND LAND RESOURCE SURVEYS OF THE REGION

Many of the nineteenth century expeditions to West Africa visited the Chad Basin. Several of these had scientific aims and collections of flora and comments on geographical features were often made. Expeditions crossing the Sahara from North to South made by Clapperton, Denham and Oudney in 1822-4 and by Rohlfs in 1873 both reached Lake Chad and collections of natural specimens, particularly flora were taken (McLynn, 1992). Unfortunately such work was not immediately followed-up, since, during the "Scramble for Africa" made by European nations in the period from 1870 onwards, military and commercial interests were of prime importance within any expedition (Iliffe, 1995). Few scientific investigations appear to have been undertaken in this geographic area until after the political boundaries of the new colonial entities were firmly established.

2.2.1 Surveys from the Colonial period

Surveys and reporting of natural resources were made by all of the Colonial powers in Africa. In the Chad Basin these were commissioned by both the British and French administrations, the British in Nigeria and the French in what are now the countries of Niger, Chad, and Central African Republic. Early (pre-1918) German surveys of Cameroon were followed by those of both British and French scientists. The earliest of the colonial surveys in Nigeria were collections of flora, of particular note is that taken by Dalziel from 1905-1912, which is the basis of the flora by Hutchinson and Dalziel (1954). Also in this early colonial period, Foster (1914) produced a catalogue of tree species in the region and classified timber resources for future exploitation and Falconer (1911) produced a broad-scale geographical and geological survey of the region. However, during this early colonial period, the soils of the Chad Basin appear to have received little attention. This is in contrast to the superficially similar Gezira Plain in Sudan, where the soils have been extensively studied since the 1920's (*e.g.* Greene, 1928). In the post-1945 colonial period, surveys started to become more comprehensive with the publication of flora catalogues and initial soil surveys in the region (Cameroon - LaPlante, 1954; Nigeria - Higgins *et al.*, 1960). Whilst there is a distinct difference between the publications of the early colonial period and this later period, with a shift in focus towards agriculture, there is little from this period concerning the soils of the Lake Chad region in Nigeria which has not been augmented or superseded by more detailed or refined survey.

2.2.2 Field surveys 1960 - 1975

In Nigeria the major detailed soil surveys of North Eastern Nigeria were undertaken in the early 1960's (Higgins, 1964; Tomlinson, 1964), with reports of these continuing until about 1975. Much of the reconnaissance soil survey was undertaken in order to produce a mapping at the 1:250,000 scale (Tuley, 1972; Carroll and Klinkenberg, 1972; Carroll, 1974). Tuley (1972), as editor, oversaw the most comprehensive land resource survey of this area to date, with a series of volumes, each devoted to particular aspects of natural resource use. In the Francophile countries, soil mapping and land resource mapping also continued after the independence of the countries concerned, principally through ORSTOM projects. Of particular interest are studies in the same type of land system in northern Cameroon. Such studies have ranged from surveys and comparison of very large areas (Pias, 1962) to very detailed descriptions (Bocquier, 1973) of soils. In order to construct a series of sampling locations in this region for the study described in this thesis, the surveys of Tuley (1972) have been used as the primary source of information on soil types and land use classification (figure 1.18).

Since this mapping was relatively comprehensive it has been used, in broad outline, in order to plan many agricultural development and irrigation projects in the region. The largest and most ambitious of these are the Chad Basin development projects, run under the auspices of the Chad Basin Development Authority (CBDA). These were planned and undertaken in the late 1970's and early 1980's. More recently, there has been a series of new initiatives, notably the North East Arid Zone Development Programme (NEAZDP) (Kimmage, 1990) which is centred to the west of Lake Chad around Gashua (12°50' N 11°05'E).

2.2.3 Field surveys 1975 - 1990

The CBDA development projects were conceived principally in order to produce crops of both wheat, with up to two crops per year, and of rice (Adams, 1992). They were not planned to increase the intensity of production of the local Masakawa sorghum crop. Three major Chad Basin development schemes have been implemented, focused on Baga, New Marte and Ngala (see figure 1.4). During the planning and pilot phases of these projects (Hansen, 1966), several detailed surveys are known to have been undertaken but are unpublished and unavailable. In this period, however, Beavington (1978) produced a study of selected profiles, highlighting certain characteristics of the profile morphology and contrasting this with the soils of the Gezira plain. Additionally, Beavington and Varley (1979), made a brief study of micro-nutrient availability for rice production on these soils. The CBDA development projects which were undertaken have had major effects on many aspects of the region, including the movement and resettlement of many farmers following the compulsory acquisition of their land by the national government (Kirscht, 1996). The extent of the CBDA projects' influence is particularly evident at the three locations, where there has been large scale construction of irrigation canals. At Baga a canal extending 29 km was constructed from Lake Chad to a series of polders. As Lake Chad receded in the early 1980's this canal was extended further but ultimately to no avail, as no water now reaches the polder fields. Similarly at New Marte and Ngala, the large-scale canal networks constructed are now of limited practical use. The failure of these Chad Basin development projects has been extensively discussed (*e.g.* Adams, 1992; Kirscht, 1996). An impression of the size of the development project at New Marte can be gauged from the water pumping station at Kironowa shown in plate 2.1.

Plate 2.1 (above)
Earth works and pumping station at Kironowa (12°26'N 13°56'E)

Plate 2.2 (left)
Profile on Lake Chad margin, close to Dongofili (February 1995)

With a lack of detailed survey information before the construction of these Chad Basin development projects and because of the extensive nature of the disturbance caused – which included the grading (levelling) of large areas of land to allow for flood irrigation – it was necessary to avoid sampling areas where such disturbances had occurred.

2.3 SEDIMENTS AND SOIL PARENT MATERIALS IN CHAD BASIN

2.3.1 Lagoonal sediments

The parent materials of the soils formed within the southern part of the Chad basin are lagoonal sediments, deposited from a receding Lake Chad, with varying depths of overlying aeolian sand. The lagoonal sediments are either sandy or clay-rich. The origin of material entering Lake Chad is dominated by the river systems to the south of the lake. The headwaters of the Alo and the Yedseram are from the Mandara mountains in Nigeria and Cameroon. The Logone (a tributary to the Chari) system also draws from the eastern side of these mountains. The Chari headwaters are located in the region around Sarh in Chad and in Central African Republic from the Bamingui - Bangoran region to the west of the Bongo massif. The geology of these mountains is described briefly by Falconer (1911) and Wright (1985). These and other more detailed surveys reveal the Mandara mountains to be dominated by basaltic igneous material, particularly olivine basalts, with the remainder of the headwater catchment for the Chari also basalt with lesser amounts of calcareous shales of marine origin.

2.3.2 Aeolian inputs

Whilst there have been several recent studies where aeolian material has been collected (see section 1.5.4), world-wide there is little published work on characterising the chemical and mineralogical composition of this material with most authorities (*e.g.* Cooke *et al.*, 1993) stating that most of the sand component of this material is quartzose.

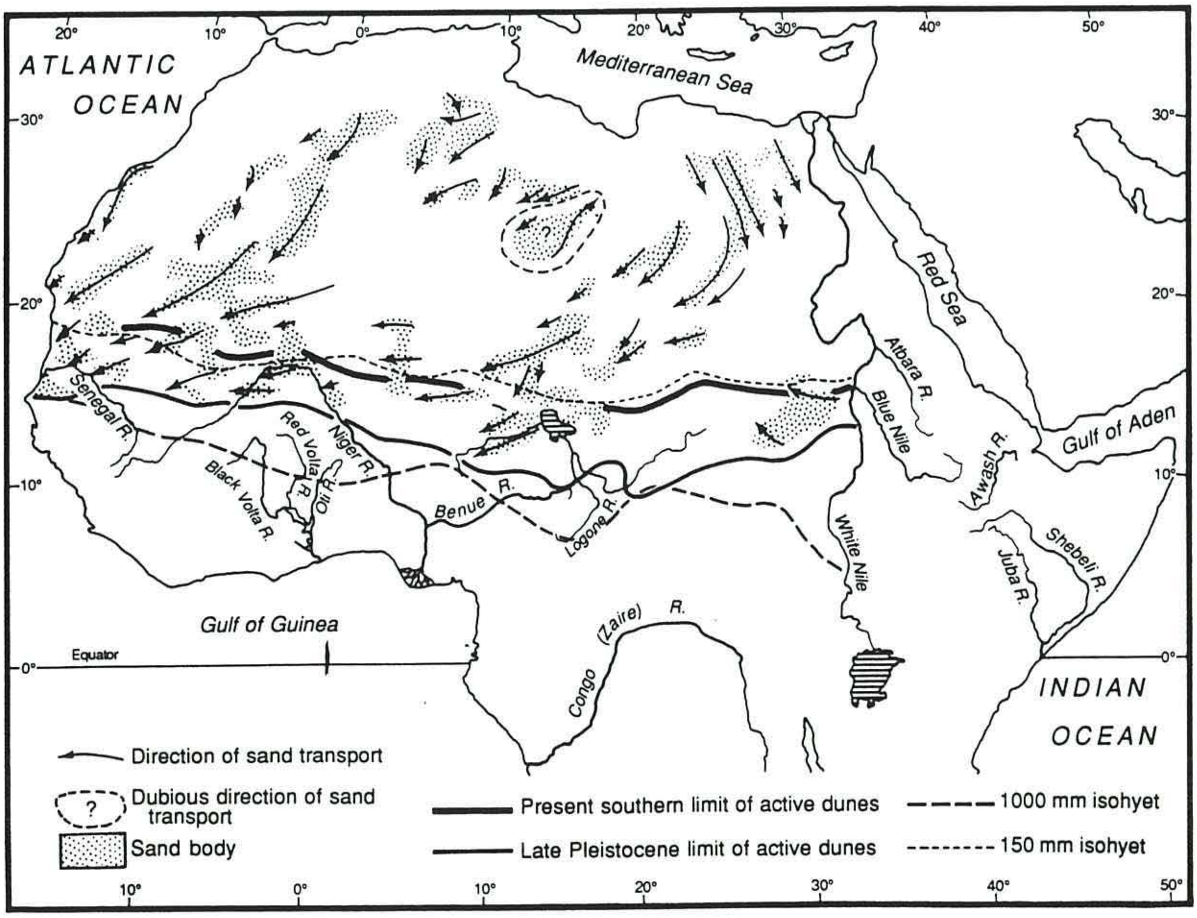
2.3.3 Sand inputs

The Chad Basin, in common with the rest of West Africa, has experienced a series of climatalogical and vegetational changes from the late Pleistocene through the

Holocene. These have interlinked with sand transport processes, principally mass-flow over the land surface and to a lesser extent saltation (Cooke, *et al.* 1993), to deposit sand bodies throughout the southern margins of the Sahara: the present day Sahel.

It would appear (Figure 2.2) that the change between the arid late-Pleistocene period and the higher rainfall period of the early Holocene caused a stabilisation of previously mobile sands by the growth of vegetation (Williams *et al.*, 1993). Despite subsequent climatic changes with rainfall decreasing relative to this early Holocene period, the area around Lake Chad has retained sufficient vegetation cover for the dunes to remain stable. In the Sahelian area immediately to the north of the region studied, sand movement is less than at other locations more central to the Sahara (Fryberger and Dean, 1979 - quoted by Cooke, *et al.* 1993). This would appear to be the result of the increased rainfall and greater vegetation cover in the southern parts of the Sahel.

Figure 2.2 Directions of sand movement from late Pleistocene period to present day (after Williams *et al.*, 1993)



2.4 SELECTION CRITERIA FOR SAMPLING LOCATIONS

2.4.1 Criteria used to select sites for chronosequence

Two main criteria were used to select a series of sites in order to describe a soil chronosequence across North East Nigeria. These are:

1) For the locations to be of different ages from their last exposure. This requires the profiles sampled to be at different radial distances from the lake (see 2.4.2).

2) Only clay-rich soils on lagoonal deposits are sampled. Around the lake there are a series of large-scale dune features, therefore selecting only clay-rich soils avoids their interference.

2.4.2 Constructing a Chronosequence

There is very little dating evidence to support particular dates for the past recession/advance events of Lake Chad throughout the Holocene. This has led to the intense debate noted in section 1.6.2. All authors acknowledge that it is difficult to establish the date of exposure, during the last lake recession, at any particular point in the exposed plain of lacustrine deposits. Dating has been limited to a small number of archaeological materials (Thiemeyer, 1992), which support the paleo-lake hypothesis of Durand *et al.*, (1984); *i.e.* that the last lake maxima was 6000 years B.P. In addition to the uncertainties in the dating of changes of the lake, similar difficulties exist in trying to deduce the spatial extent of past lake maxima and minima. The only boundary readily recognised is that of the Bama ridge which is considered to represent the greatest extent of the lake, a hypothesis first expressed clearly by Grove and Pullan (1963).

To construct a chronosequence of soil development within this 6000 year period, a relationship was assumed to exist between the radial distance of a site from the current lake and the date of the exposure of this site after the last lake maxima. Obviously, this relationship cannot be assumed to be linear, due to both past-climatic changes and to the fluctuating topography. With these considerations, the chronosequence was constructed, with the twin constraints of (i) working within the political borders of Nigeria, and (ii) limiting the study to four sampling positions.

With the field experiment at New Marte established, one position within the chronosequence was already determined. Whilst a sampling regime involving clustered sampling would give an estimate of the variation of the profiles and allow for the definition of a "typic" profile, logistical problems restricted the sampling to three individual profiles (Figure 2.3 illustrates their relative positions to Lake Chad):

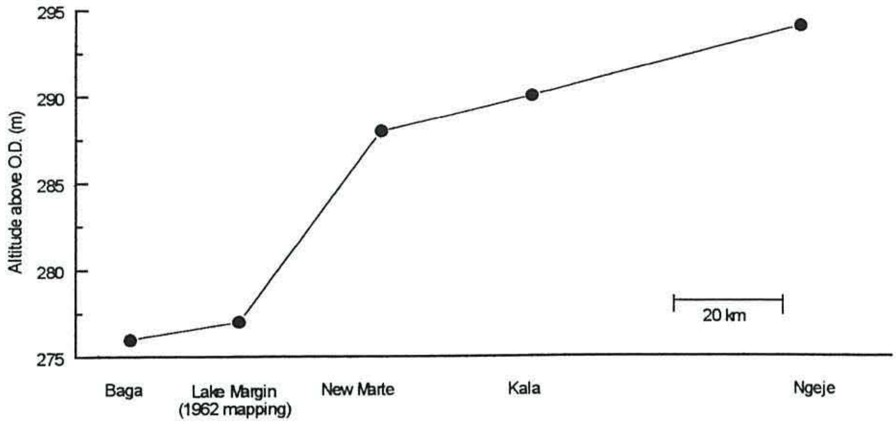
1) a position between New Marte and the current lake. Since New Marte is relatively close (40-50 km) to the current lake margin, a "starting" position was selected on the margin of the current lake from which the lake had only recently (*ca.* 10-15 years) receded. The most accessible position was gained by travelling from the major fishing-based town of Baga.

2) a position in an area where the surface was exposed earlier than at New Marte. Using the land systems map (see Figure 1.18), a position in the Kala clay plains, part of the "Chad Lagoonal Complex" was selected to represent this situation. The site chosen was near to the settlement of Kala, a trading centre in the Firki plains. The Firki plains have recently been the subject of several archaeological studies, with excavations on settlement mounds (Gronenborn *et al.*, 1995) similar to that upon which Kala is built. These studies may yield information on past lake events and therefore reinforce this work, dating the period of exposure of this location.

3) a position in an area with a surface exposed earlier than both New Marte and the Kala site. Using the Land Systems mapping (Figure 1.18) again, a position in the Ngeje clay plains area was selected. This represents the last large clay plain, remaining exposed, on a radial axis from the current lake toward the Bama ridge, before reaching the extensive stabilized dune fields, referred to by Tuley (1972) as the "Chad longitudinal dune field", which surrounds the settlement of Gulumba Gana (11°45'N 14°05'E). A suitable position within the clay plain was found close to the deserted village of Ngeje.

With the exception of Ngeje, all of the profiles sampled were at locations where some form of agricultural activity had been undertaken. At Baga this was the cropping of field beans, an important cash crop. At New Marte and at Kala, masakwa was cultivated. At Ngeje the area around the profile sampled had, according to local sources, previously been used for masakwa cropping although cropping had ceased some time (*ca.* 20 years) ago with the abandonment of the village. The local people had then moved to a new location, Gazalful (11°48'N 14°36'E), where the supply of potable water is considered more reliable.

Figure 2.4 Radial distance to site locations from margin of Lake Chad



2.5 FIELD DESCRIPTIONS

Positional information was obtained using Garmin GPS - 75 (Global Positioning System) equipment which, with "standard positioning service" rather than the US military's "precise positioning service", has a quoted minimum precision of +/- 300 m (D'Oliveria and Featherstone, 1995). In practice, it was found that positions could be relocated to a precision of +/- 20 m. This was particularly important when a return trip was made to the Baga site (see 2.5.1) in February 1995 where, with reference to other landmarks, the GPS was used to relocate the then inundated site. GPS was also used to assess the relative altitude of a particular location but this was found (±100 m), when compared to mapped heights (±5 m relative to O.D.), to be an inaccurate method of assessing altitude relative to ordnance datum.

The three locations identified in addition to New Marte for the construction of a soil chronosequence were examined, described and sampled for chemical analysis during the field season of 1993-1994. The altitude of the sites quoted is from the 1964 Nigerian Federal survey mapping at 1:50,000. Profiles were dug and described according to the SSEW procedures of Hodgson (1976), with only minor modifications to the field practice outlined. Compression strength tests were made on the New Marte profiles using an Eijkelkamp (model 06.03) hand-held penetrometer

(Giesbeek, Netherlands). Other authors in the tropics have used a variety of field handbooks including those by FAO (FAO, 1968) and USDA (Soil Survey Staff, 1951) and the national soil surveys of Australia, Germany and France. The lack of a common guide is acknowledged (IBSRAM, 1987) as a cause of problems in managing pan-national studies such as the IBSRAM vertisol network.

2.5.1 Baga

Various sites were examined and sampled in order to represent the soil developing at the margin of the current Lake Chad. In order to achieve this a speculative sampling trip was undertaken from Baga along part of the Chad Basin development project canal (see section 2.1.1) towards the more open water of Lake Chad. The term "open water" is used by local fishermen and military forces for the area of the lake where there is permanent water and movement by boat is unrestricted by vegetation (*i.e.* deep permanent water). This trip was undertaken in June 1993, when the political situation between the countries surrounding the lake necessitated an armed escort from Nigerian military and police forces, which in particular restricted photography. When a return trip was made to the Baga sampling sites in February 1995, it was found that the water level of Lake Chad had risen by 1.7 m from the previous visit. This had led to widespread disruption and repositioning of many villages and settlements. On this later visit photography was allowed. Plates 2.3 and 2.4 show the relief of the area.

The sampling trip in June 1993 led to more detailed examination of two of the sites where profiles were dug. Numerous auger samples were examined in an attempt to arrive at a typical profile. The two profiles selected represent the soils developing on the lake margins, this may be a considerable distance from the "open water" little of which lies within Nigerian territory during years of low rainfall. The groundwater in this area rises throughout the rainy season and for several months beyond the cessation of the rains, reaching a peak in December/January. This means that these sites are wet or flooded for a considerably longer period than the other locations sampled.

Plate 2.3 February 1995 - Sampling at Dongofili, water level 1.7 m above that recorded in June 1993

Plate 2.4 Bean field at Kawatar Kuate - February 1995

Profile "Baga 1" at Dongofili

Sampling date: 8 June 1993
Relief : level (*i.e.* < 1% change vertical : horizontal)
Altitude : 277 m O.D. from 1962-4 Federal survey mapping
Location : Dongofili (13°11.44'N 13°53.46'E)
Surface vegetation : mixed hydrophytic plants - due to be weeded and planted with beans
Special features of site : seasonally inundated for varying periods towards end of rainy season when lake level rises. Dongofili is a small trading centre in cross-border goods including cattle. Area subject to trampling and puddling due to cattle movements. There is no evidence of soil fauna activity at the site.
Weather conditions : bright overhead (12.15pm) sunshine with SW wind. Start of rainy season, although no rain for previous two days.

Depth (cm)	Zone	
0 - 4	1	Purplish? black (5RP 3/1?) Organic rich (little mineral content); Decaying plant leaf material; roots numerous fine (1 - 2 mm) fibrous roots and medium (2-5 mm) fleshy roots; wet; porosity very high; lower boundary distinct
4 - 6	2	Black (5Y 2/1) Organic rich (H_2S evident by smell); Clay texture, massive structure; firm consistency; wet; porosity <0.5%; roots 10-15%, (medium woody and fine fibrous); lower boundary wavy 1-2 cm
6 - 23	3	Brownish black (10YR 2/3) Organic rich; clay texture; massive structure; wet, firm consistency; porosity <0.5%; roots 5-10 % fine fibrous
23 -water table		

Profile "Baga 2" at Kawatar Kuate

Sampling date: 8 June 1993
Relief : level
Altitude : 277 m O.D.
Location : Kawatar Kuate (13°09.71'N 13°51.85'E)
Surface vegetation : Cultivated beans (see Plate 2.4)
Special features of site : seasonally inundated for varying periods towards end of rainy season when lake level rises. Kawatar Kuate is a small settlement where agriculture is a more established activity than at other locations nearer the lake. There is no evidence of soil fauna activity at this site.
Weather conditions : Bright overhead sunshine (12.15pm) (colours difficult to assess) with SW wind. Start of rainy season, although no rain for previous two days.

Depth (cm)	Zone	
0 - 6	1	Dark brown (7.5YR 3/3) with distinct mottles Brown (7.5YR 4/6); organic rich - clay to loamy clay texture; weakly developed granular structure; loose consistency; roots 2-5% with fine fibrous roots; wet; very porous; lower boundary distinct
6 - 18	2	Brown (7.5YR 4/3) mottled (30%) Brown (7.5YR 4/6); clay texture, massive structure; loose consistency; moderately porous; roots 10-15%, (medium woody and fine fibrous); lower boundary wavy 1-2 cm
18-30	3	Dark brown (10YR 2/3) uniform colour throughout zone; clay texture; massive structure - evidence of slickensides; wet, firm consistency; slightly porous; roots 5 % fine fibrous only (extending from surface)
30 - water table		

The major difference between the soils of these two locations, indicated by the mottling and the friable structure of the upper horizon at Kawatar Kuate is increased aeration. This change was also indicated by the samples taken by auger between these two sampling points. The profile at Dongofili represents the extreme fringe of the area where some form of agriculture is practised, with the lake at the level found in 1993/4. The site at Kawatar Kuarte is representative of a much greater area, slightly inland from the lake. Here agriculture is more stable and the period of inundation when the lake level rises is likely to be shorter, thereby allowing for a longer period of cropping. Although crops which require a longer period to grow than field beans could be grown in this area farmers prefer to grow several crops a year of high value produce such as field beans, cow pea and onions.

2.5.2 New Marte

The site at New Marte is at the western fringe of the area where masakwa is cultivated. Directly to the west of the site, the lagoonal sediments are covered by increasing depths of overlying surface sand. This factor, combined with an elevation slightly higher than that of New Marte which reduces the amount of water retained after the rains since there is greater run-off, results in an area where little or no crops are grown. The New Marte site itself varies between soils with sandy surface (Plate 2.5) and those with a clay-rich surface (Plate 2.6). With the imposition of a tree planting scheme for agroforestry experimentation on this site, it is important to compare these different soil types. For this purpose three profiles were dug and described at New Marte. The first of the three profiles represents the sandy variant of the soil on this site (Plates 2.7 and 2.8). The third, the clay variant, whilst the second profile is an intermediate between these two extremes.

The vegetation surrounding the site is characterised by relict trees and much bare ground in the dry season, despite the area being a gazetted forest reserve. In some places the bare surface reflects the die-back of annual hydrophytic communities as standing water has receded or evaporated, in other positions the bare surface is the result of general land degradation or aeolian sand accumulation. In the lower vegetative strata dominance varies to some extent between Cyperaceae, *Sphaeranthus* and *Acanthospermum* with other weeds. Whether underlying site conditions or gregarious behaviour have produced this effect is not clear; what remains of the tree cover is too scanty to reveal corresponding patterns.

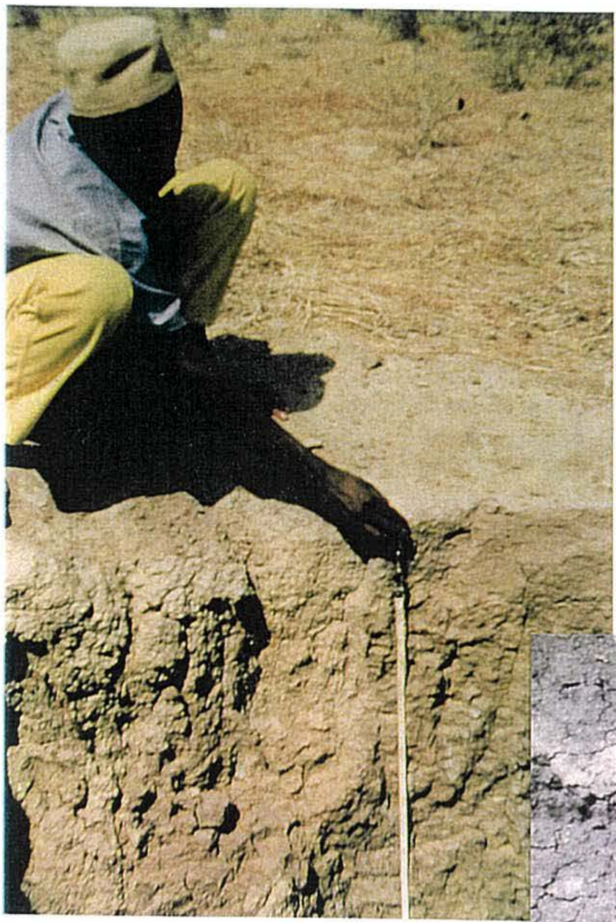


Plate 2.5 (left)
Soil profile at New Marte field site with a crusted sandy surface

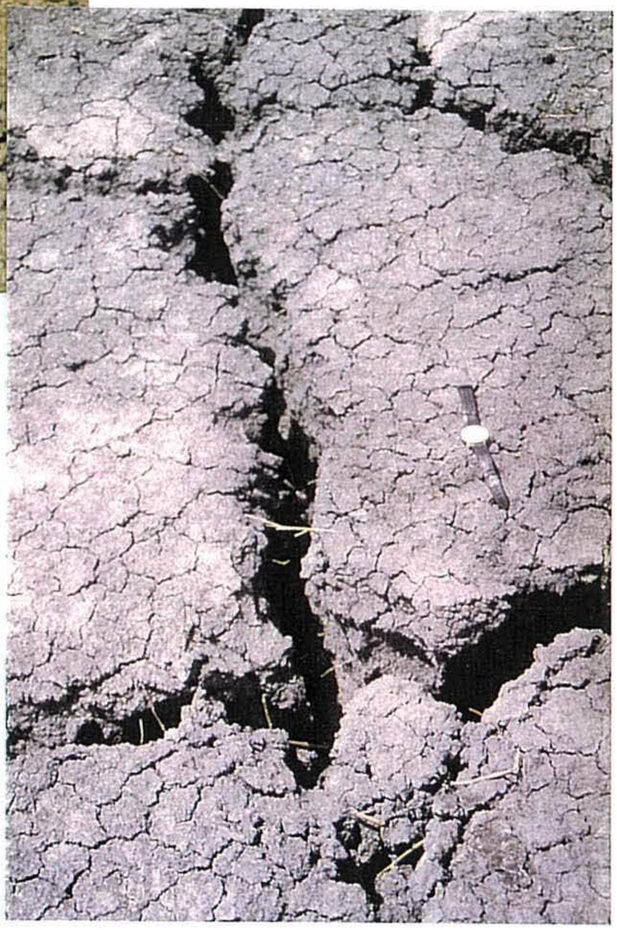


Plate 2.6 (right)
Polygonal cracking of soils with clay-rich surface at New Marte (wrist-watch for scale)

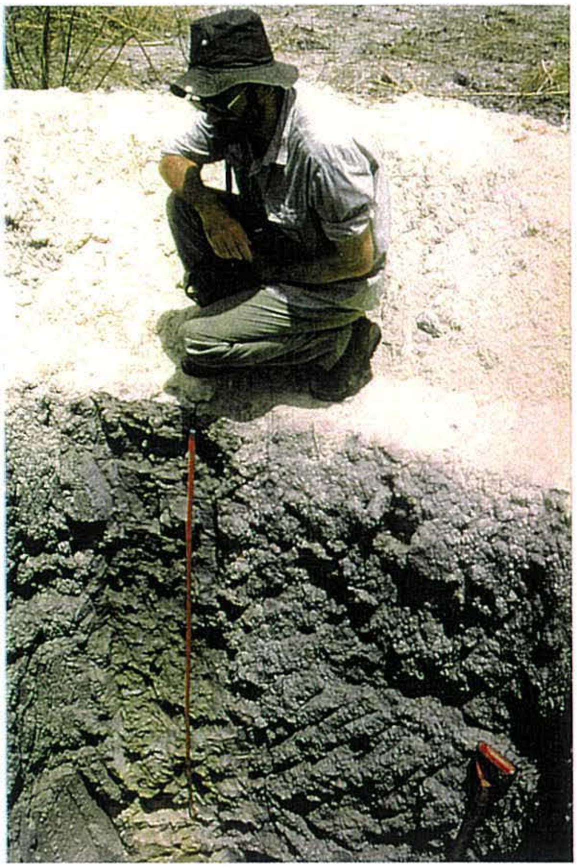


Plate 2.7 (left)
Soil profile NM 1

Plate 2.8 (right)
Detail of soil profile NM 1 - upper 70 cm shown with cracking extending to 50 cm from surface

New Marte Profile "NM1"

Sampling date: 25 May 1992
Relief : level
Altitude : 288 m O.D. (from 1964 Federal survey mapping)
Location : New Marte Agroforestry Experiment Profile NM1 - Location, plot 125
Conditions: dry, no rainfall since October 1991, direct overhead sun, very hot (38°c +)
Surface vegetation : dead grasses - no trees taller than 1 metre within 25 metres of the sampling pit. Surface cover at yearly minimum since this period is at the end of the dry season.
Drainage: poor due to heavy texture
Special features of site : represents the sand-rich surface soils of New Marte field site. Whilst monitor lizards are present in other sand-rich soils there is no evidence of their burrows at this location. Termites and ants present on soil surface. Plant debris on soil surface consumed by termites and covered by cemented soil material. No evidence of cracking on the soil surface.

Depth (cm)	Zone	
0 - 0.5	-	Laminated surface crust with smooth surface. Pinkish grey (7.5YR 7/2) (loamy?) fine sand; dry.
0.5 - 8 or 9	1	Brown (10YR 5/3) (loamy?) fine sand; loose, breaking to a very weak fine granular structure; dry; porosity 0.5%;roots 2-5%, (fleshy 1mm diameter and fine fibrous); lower boundary invaginated into Zone 2 as much as 12 cm; invaginations 2 cm wide.
8 or 9 - 17 or 21	2	Greyish brown (10YR 5/2) (loamy?) fine sand with thin (0.1 cm) darker bands (10YR 4/3) and (10YR 5/2) at base; narrow (0.5 cm) laminations and oblique, irregular channels; loose, breaking to very weak, fine granular structure; dry; porosity 0.5%; roots as Zone 1; sharp lower boundary.
17 or 21 - 27 or 30	3	(10YR 5/2) loamy fine sand; weak angular blocky (5cm) breaking to weak fine granular; dry; porosity 0.5-1%; stronger than zones 1 and 2; fleshy and fine fibrous roots (1%); merging lower boundary.
27 or 30 - 43	4	Dark greyish brown (10YR 4/2) sandy loam; well developed prismatic structure (7cm crack to crack) breaking to well developed angular blocky (2-3cm) structure; clay-rich and hard; dry; porosity 0.5-1%; roots restricted to cracks (fleshy and fine fibrous); very rare woody roots; merging lower boundary.
43 - 95	5	Dark greyish brown (10YR 4/2) (fine sandy?) clay; structure is continuation of zone 4, but diminishes with depth; breaks to strong angular blocky; dry; porosity <0.1%; very fine fibrous roots; no fleshy roots; merging lower boundary.
95 - 125	6	Brown (10YR 5/3) (fine sandy?) clay with irregular shaped infilling with paler greyish yellow material (2.5Y 7/2); no obvious structure, but massive breaking to weak angular blocky; dry; porosity 0.5%, macropores along root channel; small number of fine fibrous roots; evidence of decayed woody roots; fine channels (<0.5cm) infilled with faecal material; white ovoid features (5-10mm) present, have no reaction with HCl and may be organic; merging lower boundary.
123 - 170	7	Light grey (10YR 7/2) loamy fine sand with 50% very coarse ovoid mottling (light brownish grey - 2.5Y 6/2); superimposed on this is 30-40% of brownish yellow to yellow (10YR 6/8 to 10YR 7/8) mottling with diffuse boundaries; small black granular nodules (not Mn), discrete and up to 0.5cm diameter; massive; dry; porosity <0.1%; very rare fine fibrous roots; large ovoid feature (coarse sand) towards base of horizon ca. 10cm diameter, concentric; merging lower boundary.
170 -200+	8	Pale yellow (2.5Y 7/4) (loamy?) fine sand with diffuse mottling <20% (10YR 6/8); massive; dry; porosity <0.1%; no roots seen.

New Marte Profile NM1 - Unconfined compression strength

Zone	Direction	Penetrometer readings (kg F cm^{-2}) and number of tests (n)
Surface crust	(vertical)	3.75 (n = 10)
Zone 1 - below crust		1.50 (n = 8)
	(horizontal)	
Zone 2 - top	(horizontal) - top	2.75 (n = 6)
Zone 2 - bottom	(horizontal) - bottom	2.75 (n = 6)
	(Zone 2 is very variable, both laterally and horizontally)	
Zone 3	(horizontal)	3.75 (n = 6)
Zone 4	(horizontal)	>4.5 (n > 6)
Zones 5 - 8	(horizontal)	>>4.5

New Marte Profile "NM2"

Sampling date: 26 May 1992
Relief : level
Altitude : 288 m O.D.
Location : New Marte field site plot number 253 (see figure 1.21)
Surface vegetation : Dead grasses - no trees within 3 m of profile
Conditions: as NM1
Drainage: poor
Special features of site : Represents the mid-position between sand-rich and clay-rich surface soils at New Marte field site. No surface cracking evident.

Depth (cm)	Zone	
0 - 6	1	Dark greyish yellow (2.5Y 4/2) to greyish yellow brown (10 YR 4/2) silty clay (loam?) (does not slake quickly) with (*ca.* 2mm) dense crust of light grey (10 YR 8/2) material; massive structure breaking to moderate medium angular blocky and medium fine angular blocky peds; dry; porosity between 0.1% and 0.5%; fleshy <2 mm roots with 0.1 - 0.5% fine fibrous; sharp level lower boundary
6 - 23	2	Brownish grey (10YR 4/1) silty clay (clay loam?) with occassional dull yellow orange (10YR 6/3) sand coatings on peds; massive structure breaking to weak coarse subangular blocky peds; dry and resistant to wetting; porosity <0.1%; fleshy <2 mm roots with <0.1% fine fibrous; merging lower boundary invaginated slightly (2-5 cm) into zone 3
23 - 85	3	Brownish black (10YR 3/2) to greyish yellow brown (10YR 4/2) clay (clay loam?) with dull yellow orange (10YR 6/3) sand coatings on peds; massive structure breaking to moderate medium angular blocky peds; dry; porosity <0.1%; fleshy <2 mm roots with <0.1% fine fibrous;merging lower boundary
85 -155	4	Fine sandy loam greyish yellow brown (10YR 6/2) matrix with dark greyish yellow (2.5Y 5/2) infilling; extensive (25 %) mottling; bright yellowish brown (10YR 6/6) mottles exhibit diffuse edges with smaller number of yellowish brown (10YR 5/8) mottles with sharp edges; occasional fine white speckles following (relict root?) channels - no reaction to HCl ; massive single grain; dry; porosity <0.1%; roots absent ;sharp lower boundary
155 - 200 + (bottom of profile)	5	Light grey (10YR 7/1) to dull yellow orange (10YR 7/2) fine sand with extensive (25 - 35 %) diffuse bright yellowish brown (10YR 6/8) mottling; massive single grain; dry; porosity <0.1%; roots absent but occasional dark (biogenic?) tubular horizontal features 10 mm diameter present

New Marte Profile NM2 - Unconfined compression strength

Zone	Direction	Penetrometer readings (kg F cm^{-2}) and number of tests (n)
Zone 1 -below crust	horizontal	>4.5 (n = 6)
Zone 2	horizontal	>4.5 (n = 6)
Zone 3	horizontal	>4.5 (n = 6)
Zone 4	horizontal	>4.5 (n = 6)
Zone 5	horizontal	3.25 (n = 4) in patches, otherwise >4.5 (n = 4)

New Marte Profile "NM3"

Sampling date: 26 May 1992
Relief : level
Altitude : 288 m O.D.
Location : Plot 378 New Marte field site (see figure 1.21)
Conditions: as NM1
Surface vegetation : relict grasses
Special features of site : Represents the clay-rich surface soils at New Marte field site. Extensive polygonal surface cracking of the soil with cracks up to 3 cm width present.
Drainage: poor

Depth (cm)	Zone	
0 - 6	1	Thin (1-2 mm) light grey (10YR 7/1) surface crust; rest of zone - fine dark greyish brown (10 YR 4/2) clay (immediately slakes upon wetting) with few (<0.5%) discrete (1mm) yellowish brown (10YR 5/8) mottles around root channels; Also present are few (<1%) discontinous but distinct horizontally oriented light grey (10YR 7/1) sand lenticles 1-2 mm thick 40-50 mm wide; fine angular blocky structure moderately developed; vertical cracks (max. 3 cm width) extending from surface to bottom of zone 2; dry; porosity *ca.* 5%; small number of woody (<6 mm diameter) and numerous fine fibrous roots; merging boundary with zone 2
6 - 22	2	Dark grey (10YR 4/1) clay with light grey (2.5Y 7/1) sandy coating to peds (peds do not immediately slake on wetting); massive structure breaking to fine/medium sub-angular blocky; vertical cracks extending to surface narrowing with increasing depth; dry; porosity < 0.1%; few woody (<5 mm) and numerous fine fibrous roots; merging boundary with zone 3
22 - 72	3	Brownish black (10YR 3/1) clay with greyish yellow (2.5 Y 7/2) sand coatings to peds; (clay slakes more quickly than zone 2); massive structure breaking strong medium sub-angular blocky peds - some laminar structures evident but no vertical cracking; dry; porosity 0.1%; fleshy <3 mm and fine fibrous roots; large (25 mm diameter) horizontal relict (root) channel present; distinct boundary with zone 4
72 - 88	4	Greyish yellow (2.5Y 7/2) with extensive (50%) diffuse bright brownish yellow (10YR 6/8 to 10YR 7/6) mottling; occassional dull yellowish brown (10YR 4/3) "breccia" infilling tubular (biogenic?) features; fine sandy clay; massive single-grain structure; dry; porosity < 0.1%; fleshy <3 mm and fine fibrous roots; merging boundary with zone 5
88 - 114	5	Greyish yellow (2.5Y 7/2) with (<20%) diffuse bright brownish yellow (10YR 6/8 to 10YR 7/6) mottling; (loamy ?) fine sand; massive single-grain structure; dry; porosity < 0.1%; few fleshy (<2 mm) and fine fibrous roots diminishing with depth; distinct boundary with zone 6
114 - 185	6	Greyish yellow brown (10YR 6/2) loamy fine sand; patchy (5%) large (5-10 cm) diffuse bright brown (7.5YR 5/8) mottles and numerous fine (2-5 mm) dark brown (10 YR 3/4) mottles following (root?) channels; massive single grain structure; dry; porosity < 0.1%; no roots evident ; very sharp boundary with zone 7
185 - 214 + (bottom of profile)	7	Irregular 1-2 mm thick light grey (2.5Y 8/2) surface below zone 6, otherwise strong angular light grey (10YR 8/1) to brownish grey (10YR 4/1) fragments; texture - loamy fine sand; dry; porosity < 0.1% ; no roots evident

New Marte Profile NM3 - Unconfined compression strength

Zone	Direction	Penetrometer readings (kg F cm^{-2}) and number of tests (n)
Zone 1	horizontal	>4.5 (n = 6)
Zone 2	horizontal	>4.5 (n = 6)
Zone 3	horizontal	>4.5 (n = 6)
Zone 4	horizontal	4.25 (n = 6)
Zone 5	horizontal	3.75 (n = 6) patchy
Zone 6	horizontal	3.75 (n = 6)
Zone 7	horizontal	>4.5 (n = 6)

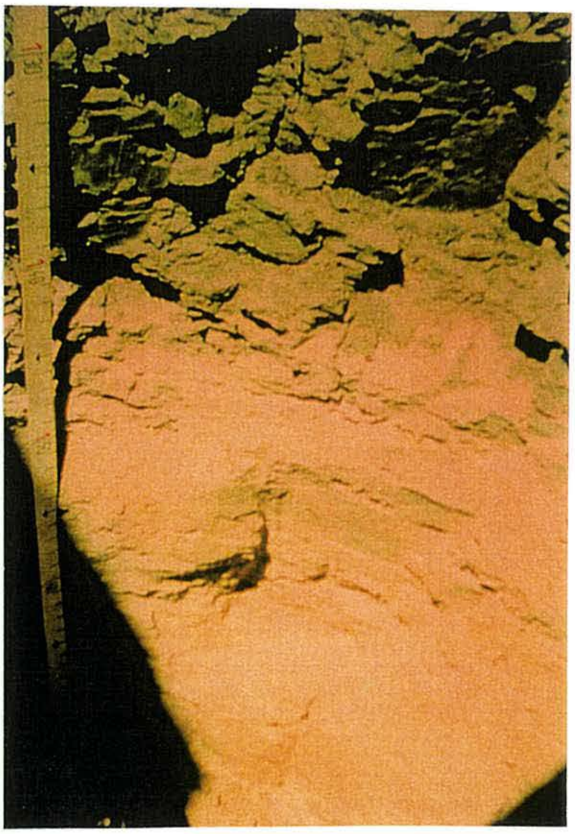
2.5.3 Kala

The sampling location near to Kala was arrived at after discussion with the village head and local farmers. Apart from locating an area under masakwa cultivation, this was particularly important since a disturbed area surrounding the whole village could also be avoided. Repeated excavations had been undertaken in order to construct and maintain the settlement mound upon which the village was built. This area where earth works had caused wholescale removal of the surface soil, covered a concentric ring with a radial distance of up to 300 m surrounding the village. Plates 2.9-2.11 show the surface of the site at Kala and details of the soil profile.

Plate 2.9 (left)
Surface of
Kala profile
showing detail
of surface
cracking

Plate 2.10 (below left)
Surface cracking near Kala profile (50 mm diameter lens cap for scale)

Plate 2.11 (below right)
Kala profile sandy-textured material at depth of 149 cm + (zones 6,7,8)



"Kala" profile

Altitude : 290 m O.D. (from Federal survey mapping)
Location : 12°05.22' N 14°28.33' E within the firki (or firgi) plains outside (*ca.* 0.5 km) the large village of Kala (Market place 12°05.04' N 14°27.95' E)
Surface vegetation : relict annual grasses, sparse (<5 ha^{-1}) relict trees including *Balanites aegyptiaca* 8 m away from profile, last masakwa crop in 1992
Conditions: soil very dry - profile took three man-days to dig, weather dry with strong gusting SW wind
Drainage: poor
Special features of site: represents area where fuel wood is extracted from the few remaining trees and where Masakwa is transplanted in years where there is sufficient rainfall. Extensive polygonal cracking on the soil surface with "micro" gilgai (35-40 cm periodicity 1 - 2 cm amplitude) features present.

Depth (cm)	Zone	
0 - 2.5	1	Grey 5Y 6/1 - 5Y 5/1; Clay texture (Loamy?) distinct sand grains; sub-angular blocky to granular structure; porosity 20%; very strong peds; vertical cracks (4-5 cm width maximum) extending into zone 2; no evidence of $CaCO_3$ crusting or other cementing agents (*i.e.* gypsum); occasional (<1%) fine fibrous roots; gradual boundary to zone 2
2.5 - 60	2	Grey 5Y 4/1; clay texture - no sand grains evident; blocky to sub-angular blocky structure; large peds (8-12 cm); porosity 5 -10% but greater at top of zone (10- 15 %) diminishing with depth; vertical cracking from surface extends to 36 cm with extensive horizontal branching of these cracks at 28 cm; numerous fine roots visible - no woody or fibrous roots evident; gradual wavy boundary to zone 3
60 - 88	3	Grey 5 Y 5/1; clay texture; structure medium rounded/platy peds; (differentiated from zone 2 by a "melange" of clay peds from 60 - 70+ cm); porosity 5-10 % where large vertically oriented cracks (not reaching surface) found; distinct lack of roots - single fine root at 63 cm; clear boundary to zone 4
88-143	4	Matrix - grey (5 Y 6/1) with many (30 - 40 %) medium sized (< 1 cm) bright brown (7.5 YR 5/6) mottles. These mottles frequently merge to single units 4- 5 cm diameter - also few (< 2 %) fine (< 0.5 cm) dull brown (7.5 YR 5/3) mottles; clay texture; no roots evident; smooth sharp boundary to zone 5
143-149	5	Dull yellow orange (10 YR 7/2); (fine?) sandy texture; structure massive; strong consistency; no roots evident; wavy (1 - 2 cm) abrupt boundary to zone 6
149-153	6	Light grey (10 YR 8/2); sandy texture; structure massive; very friable consistency ("floury"); no roots evident; smooth sharp boundary to zone 7
153-171	7	Matrix light grey (10 YR 7/1) to dull yellow orange (10 YR 7/2) with few (< 2%) very fine (< 2 mm) bright yellowish brown (10 YR 7/6) mottles; sand texture with small number (<1%) "globules" of clay material - possibly relict faunal burrows; massive; strong consistency; smooth sharp boundary to zone 8
171-178+ (bottom of profile)	8	Dull yellow orange (10YR 6/4) to dull brown (7.5YR 5/3); sandy texture; massive; hard; no roots evident

2.5.4 Ngeje

Travelling from Kala to Ngeje there is a general decrease in population, and access by road vehicles is difficult. Large stands (2-3 km long by *ca.* 1 km wide) of mixed *Acacia sp.* were present in this locality, greater than at any of the other places which have been sampled. The Ngeje sampling site was selected after considering a variety of positions in the area surrounding the deserted village. Five augered samples were examined, all uniform, before the profile site was dug. Deep polygonal cracking was seen on the soil surface (Plate 2.13) and micro-gilgai features with an amplitude of up to 4 cm and a periodicity of up to 70 cm clearly evident. Plate 2.12 shows the site surface vegetation and the polygonal cracking clearly with the micro-gilgai features less distinct and plate 2.14 shows the profile described below.

"Ngeje" Profile

Sampling date : 6 February 1994
Relief : level
Altitude : 294 m O.D. (from mapping)
Location : 11°44.52' N 14°33.92' E on a level site 500-600 m away from the deserted settlement mound of Ngeje
Conditions: weather dry - no rain since October 1993, bright overhead sunshine, light SW wind
Surface vegetation : relict annual grasses (<10% cover), no trees within 100 m radius.
Drainage: poor
Special features of site : surface shows distinct polygonal cracking (see plate 2.13) with "micro" gilgai (60-70 cm periodicity 3 - 4 cm amplitude) features.

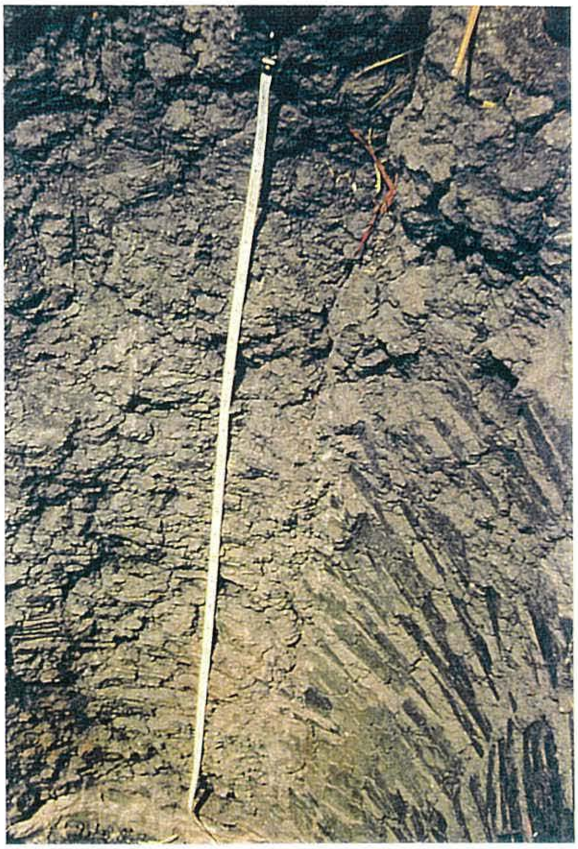
Depth (cm)	Zone	
0 - 35	1	Matrix yellowish grey to dark yellowish grey (2.5 Y 5/1 - 2.5 Y 5/2) with small (<2%) distinct fine reddish brown (2.5 YR 4/8) mottles; clay texture with sand grains; sticky and plastic when wet; structure medium angular blocky; wide (4 - 7 cm) vertical cracks with smaller number of narrow horizontal cracks; < 2 % medium size pores; very hard consistency - firm when wetted; many fine roots with occasional medium fibrous root; clear and smooth (1 - 2 cm fluctuation across profile) boundary to zone 2
35 - 62	2	brownish grey (10 YR 5/1) to dark yellowish grey (2.5 Y 5/1) no mottling except along occasional root channels; clay texture with few sand grains; sticky and plastic when wet; structure strong fine-medium sub angular blocky peds firm when moist; very hard consistency when dry - sticky when wetted; narrow vertical cracks and lesser amount of horizontal cracking; < 2% medium pores associated with root channels; surface debris evident in cracks to top of zone 3; numerous fine roots no fibrous or woody roots evident; gradual and wavy (3 - 5 cm) boundary to zone 3

62 - 95	3	Matrix greyish yellow brown (10 YR 4/2) with few small distinct reddish brown (2.5 YR 4/8) and few small faint yellowish brown (10 YR 5/6) mottles; clay texture with no sand grains evident; structure small-medium sub angular blocky peds strong; < 0.1% porosity; slickensides (1-3 cm) with weak to moderate development; very few small - medium rounded $CaCO_3$ concretions; occasional vertical crack traced to surface; zone appears to be naturally moist; no evidence of roots present; clear, wavy (3 - 5 cm) boundary to zone 4
95 - 150	4	Matrix dark greyish yellow (2.5 Y 5/2) with many (>40%) prominent medium reddish brown (5 YR 4/6) and dark reddish brown (5 YR 3/6) mottles; clay texture, no sand grains evident; structure platy with coarse (5-10 mm thick) medium-sized strong plates, showing strongly developed medium-sized slickensides; consistency firm when moistened; plate surfaces occasionally coated with light grey (10 YR 8/1) powder (not $CaCO_3$); very small number of small rounded $CaCO_3$ concretions; porosity <0.1%; zone appears to be naturally moist; no evidence of roots present; abrupt and smooth boundary to zone 5
150 - 156	5	Matrix greyish yellow brown (10 YR 4/2) with common clear medium-sized reddish brown (5 YR 4/6) mottles; texture clay; consistency plastic and sticky when wet, very hard when dry; structure platy with coarse medium plates, showing strongly developed medium-sized slickensides - fewer in number than zone 4; evidence of small (2-5 mm diameter) (worm?) "tubules" extending vertically 2-4 cm from zone 6 - contents light grey (10 YR 7/1) sandy; upper surface of plates coated with dull yellow orange (10 YR 7/2) silty films (not $CaCO_3$); no roots evident but small number of linear matted fungal hyphae (possibly pseudomycelia) present; abrupt and smooth boundary to zone 6
156 - 163	6	Matrix light grey (10 YR 8/2) with common (10-20%) fine diffuse bright yellowish brown (10 YR 6/6) mottles; (fine?) sand texture; structure massive; loose consistency; no roots evident; abrupt and smooth boundary to zone 7
163 - 172+ (bottom of profile)	7	Matrix dull yellow orange (10 YR 6/3) with few (<2%) fine distinct bright reddish brown (5 YR 5/8) mottles; texture sandy clay loam; friable when moist, hard when dry; structure massive (apedal) with small number of fine-medium (0.5-5 mm diameter) pores with distinct dark reddish brown (2.5 YR 3/6) coloration; no roots evident

Plate 2.12 (left)
Ngeje site showing surface vegetation - polygonal cracking of soil surface evident as dark lines in foreground

Plate 2.13 (below left)
Surface cracking near Ngeje profile (50 mm diameter lens cap for scale)

Plate 2.14 (below right)
Ngeje profile (total depth 180 cm)



2.6 SUMMARY OF FEATURES IDENTIFIED BY PROFILE DESCRIPTION

2.6.1 Soil profile stratigraphy and parent materials

A number of similarities exist between the seven profiles at the four sites studied. The general stratigraphy of a clay layer overlying deeper sand layers is apparent in all of the profiles which were excavated deeper than 1 m. However, the amount of aeolian sand overlying the clay layer varies between locations. All profiles show features due to the presence of water within the profile, as would be expected, since internal drainage through the soil matrix is obviously impeded in clay layers. The profile descriptions also reveal a number of distinct differences, some of which may act as indicators of the period over which each soil has developed (*e.g.* texture, surface structure, gilgai features, cracking), whilst others have implications for agricultural plant growth (*e.g.* water regime, cracking, development of anoxic conditions).

The profile sites are spread over a geographical distance of >175 km and extend radially from the shore of Lake Chad to a distance of 110 km. Over such an expansive area it would be normal to expect a wide range of parent materials. In this geographic situation it would appear that the large size of the Chad Basin, the consistent composition of the input from the river systems and the near level topography have all combined to produce near uniform parent materials for the sites studied. The variation in the depth and thickness of the deposited layers is accounted for by changes in the speed of the advance/recession events of Lake Chad. All authors who have described profiles in the area from Higgins *et al.* (1960) to Nwaka (1989), report similar (aeolian sand – clay – sand) stratigraphies and similar parent materials.

Despite the uniform parentage, the texture, structure and consistency of the surface of the profiles differs considerably, from a the wet, puddled surface at Baga through varying amounts of overlying sand at New Marte to the deeply-cracked exposed clay surfaces at both Kala and Ngeje. The surface sand at New Marte is coupled with a thin surface crust which offers resistance to penetration of the same order as similar but more intensively studied soils in the United States (Hillel, 1972). Several mechanisms have been suggested for the genesis of surface crusts including slaking, dispersion, compaction, and washing-in of material (McIntyre, 1958, Bresson and Valentin, 1994). The soils at New Marte are subject to prolonged wetting, direct intense rainfall, and over-land flow which respectively may be considered to induce slaking, compaction and washing-in. From field evidence there is, therefore, no single identifiable mechanism for the formation of the crusts found on these soils. In soils with even minor surface crusting, the sealing of the surface is recognised to inhibit water permeability and limit crop growth, particularly the emergence of seedlings.

2.6.2 Water regime

The seasonal water regime found at the Baga sites leaves the profiles wet for considerably longer periods of time than the soils at the other sites. This is partly directly due to the seasonal rainfall, but mostly from water draining to Lake Chad and the consequent rise in the lake level, which either floods the site (1994/5) or raises the water table to just below the soil surface (1993/4). When the soil can be planted with crops, these are normally quick- growing "cash-crops" such as field beans, which can be repeatedly grown in one year. Since there is normally an abundance of water when these crops are planted, there is no large expansive root network to directly stabilise the soil. The other sites have more limited periods where water is available for plant growth, reducing the effect that these plants have on soil stabilization. The masakwa cultivation systems where water is managed through the use of bunds, produces large amounts of above-ground growth but this is removed for fodder. Elsewhere in the region, land unproductive for cropping is left fallow with some growth of trees and shrubs; these tree resources are being increasingly exploited for firewood.

There is evidence that root channels are exploited by termites and are important channels for water infiltration through macro-pore flow (Holt *et al.* 1993). A few of the channels seen appear to be decayed root features, and are seen in the New Marte, Kala and Ngeje profiles suggesting that these areas were once afforested. Other, more numerous, tubular channel features seen in these three sets of profiles appear to be burrows made by lake fauna, possibly infilled by faecal material. These faunal features appear to have been inherited from the lacustrine environment. Despite features such as these channels and large scale cracking, the site drainage of these three sets of profiles would appear to be poor, since the topography is relatively flat also the clay layer of these profiles is relatively impermeable. This leads to the excess water standing on the soil surface due the difficulties of the site drainage on flat terrain (Beavington, 1978) and the growth of hydrophytic plants after the onset of the rainy season. The anoxic conditions that develop with this standing water, are one limiting factor when selecting possible tree species for planting in these areas (von Maydell, 1990).

2.6.3 Soil structural characteristics

The three profiles that have developed soil structural characteristics (New Marte, Kala, Ngeje) all show various forms of vertical cracking from the soil surface through the clay layer. Such cracking is considered to inhibit the growth of woody plants by disrupting root extension and growth (Probert *et al.*, 1987). There are clear differences in the type, quantity, depth, and width of cracks of these profiles. The profiles at Kala and Ngeje show deep cracks which extend vertically from the surface through to the base of the clay layer, whereas the cracking at the New Marte NM3 profile with the clay rich surface is limited to the upper part of the clay layer. On this profile cracks extend horizontally beneath the clay layer, indicating a different bed of clay, which possibly occurred on deposition. The other two New Marte profiles show more limited vertical cracking through the clay layer. From field-texture assessment this would appear to be due to the intermixing of the clay layer with the sand layer above, reducing the shrink/swell phenomena required to generate cracks and surface features such as "gilgai".

The term "gilgai", taken from its Australian vernacular meaning of "small waterhole", has been used in soil science as a term relating to the distinct surface relief found on many vertisolic soils, where deeply cracked soils have spatially periodic depressions and elevations of their surface. The generation and physiography of gilgai features has been extensively discussed (*e.g.* Grant and Blackmore, 1991; Edelman and Brinkman, 1962) and their effects on land use (*e.g.* McGarry, 1990) considered. Gilgai are normally associated with features where the periodicity between depressions and elevations in the soil surface is in the order of 3 to 50 m and the difference in elevation from a few centimetres up to 2 m. At Kala and at Ngeje the periodicity is less than 1 m and the difference in elevation 2-5 cm. Such features have been described at other locations in Nigeria (Nwaka, 1989), prompting the use of the term "micro-gilgai". Nwaka (1989), reporting on a range of soil profiles across northern Nigeria, identified the depth of the clay layer as the major determining factor in the size of the gilgai features developing. For the profiles presented here, however, both the clay layer and the period of exposure vary, suggesting that both of these factors may be involved in the development of gilgai. It has also been suggested (Edelman and Brinkman, 1962), that an important pre-requisite for development of gilgai are rapidly-drying lacustrine or palustrine conditions when the clay is deposited. These conditions do not allow the clay body to "ripen" before irreversible physical changes on the first drying cycle occur.

The lack of any gilgai relief at New Marte therefore seems to indicate several possible conditions of the clay deposition at this site. Firstly, the depth of the clay layer is much smaller than that at found at Kala and Ngeje, and this alone could account for the lack of gilgai features. Secondly, water-logged conditions may have allowed changes in the physicochemical condition of the clay ("ripening") to have occurred, and this would also appear to preclude the development of gilgai. Since the interplay between all of these factors is complex and the process of clay "ripening" little understood (Drever, 1985) it would appear that any index-based factors, such as the presence or absence and the magnitude of gilgai, would not be a good surrogate for the quantitative measurement of pedogenic soil structural changes.

2.6.4 Classification of soils

The soil profiles can be classified according to the USDA Soil Taxonomy system (Soil Survey Staff 1975, 1994) using the soil profile descriptions and meteorological information (see section 1.5). The two profiles at Baga are classified as Ustic Aquepts since they have not developed structural features are their water regime is such that they do not dry out for longer then six months in the year. The NM1 and NM2 profiles at New Marte are classified as Ustic Aquicambids, since although they show some development of vertisolic features these are insufficient to be classified as vertisols in Soil Taxonomy. At New Marte the more developed vertic profile NM3, along with the profiles at Kala and Ngeje are classified as Usterts.

2.7 SUMMARY OF CHRONOSEQUENCE FEATURES

From the mapped altitudes of the profile locations the chronosequence is also a toposequence with a small increase in elevation between the sites with increasing age. The total increase of 14 m in altitude over 178 km horizontally represents a slope of less than 1:12,000. This means that small changes in the lake level can influence very large areas of the Chad basin and that surface fluctuations in the order of 1-10 m are significant features for both water movement and for indicating past depositional events.

The topographic differences between the profiles appear to have a major influence on the water regime that each site experiences. This in turn, influences the soil chemistry down each of the profiles. The seasonal fluctuation between wet anoxic and dry aerated conditions would appear to be evident in the mottling and colour changes seen in the clay-rich layers, with the colour changes due to iron oxidation, rather than organic matter or manganese deposits. There appears to be a trend in the depth at which this occurs and this is likely to be evident in other chemical parameters. It was expected that the deposition of calcium carbonate, which is mentioned in previous studies (*e.g.* Higgins, 1964), would be a distinctive indicator of the depth of the water table, but in these profiles there is little field evidence for its presence.

The depth of occurrence and thickness of the clay layer also appears to form a trend within the chronosequence, with progressively thicker deposits with age. The most distinct trend from the field observations, however, is the change in soil structure, particularly the cracking and the strength of the peds. This ranges from the Baga profiles where the soils are massive and structureless to the cracked vertic soils with strong highly developed peds at Ngeje. Between these two extremes, the clay-rich NM3 profile at New Marte and the Kala profile have increasingly developed peds and vertic features. The input of aeolian sand is seen as a major pedogenic factor in producing the range of surfaces and variation in the vertical cracking seen in the three New Marte profiles. It would appear that aeolian material inputs increase towards the western fringe of the area studied, ending with the stabilised dune system seen 20-30 km west of New Marte.

Despite the visual trend in soil structural development, it would appear that more detailed quantitative measurements are required in order to comment on the soil samples taken from the New Marte field experiment. The following chapters discuss these further measurements, in particular how other soil samples from New Marte compare to the profiles that have been described in this chapter and where they may be coming-from or going-to in respect of their structural development.

3 LACUSTRINE DERIVED SOILS OF THE CHAD BASIN: (B) LABORATORY DESCRIPTION OF CHRONOSEQUENCE SAMPLES

3.1 INTRODUCTION

Following the visual description of a chronosequence of soils developed on the lacustrine clays of the Chad Basin, this chapter reports the results of a selection of chemical, mineralogical, and physical measurements made on samples taken from the profiles described in chapter 2. This is undertaken with the aim of producing more detailed information which can be related to any soil changes due to tree planting, in particular physical changes, occurring in plot-level experiments at the New Marte agroforestry site (Chapters 5, 6 and 7). These physical characteristics may indicate the condition the soils at New Marte may be coming-from and going-to as their structure develops.

3.1.1 Chronosequence description

The excavation and description of the series of sampling positions within the lacustrine clay deposits of North East Nigeria has shown an apparent chronosequence (section 2.4.2). The selection of the sites was made in order to sample locations representing a wide range of soils developed from lacustrine parent materials over varying periods of exposure as Lake Chad has receded. From the examination and field description of the profiles (Chapter 2), it was concluded that distinct physical characteristics (*i.e.* gilgai, polygonal surface cracking) have become evident and more pronounced in the older profiles at Kala and Ngeje. This trend is reflected in the USDA classification of the chronosequence soils (see section 2.6.4) from inceptisols (Ustic Aquepts) at Baga to vertisols (Usterts) at Kala and Ngeje.

In order to further characterise these soils, this chapter discusses a series of physical and chemical measurements made in order to study the factors characterising and affecting the pedogenesis of the soils found within this chronosequence. These measurements include both direct measurements on soil samples taken from the profiles (Chapter 2) and measurements of other factors that may influence pedogenesis.

3.1.2 Measurements

The main physical measurements have been made to assess the range of textures (particle size analysis) and, with a range of clay contents evident, the shrinkage of the soils as they dry. The type of clay is of key importance to this latter assessment and has been investigated using mineralogical analyses. The chemical measurements undertaken were selected in order to complement this physical information and are of interest to both studies of pedogenesis and agricultural nutrient status, respectively discussed in this chapter and in chapter 8. Several of the methods used in these analyses are used extensively in experiments described in later chapters (*e.g.* aggregate stability - section 6.6). These methods are therefore described in this chapter in detail, even though relatively small numbers of measurements have been performed on the soil chronosequence samples.

3.1.3 Local soil names

Variations in the character of the soil surface and difference in the soil's ability to be used for agricultural purposes gives rise to the naming of soils in this region by local farmers. As such, the local soil names act as an integration of all the properties of the soils, albeit with an agricultural focus. This leads to a greater number of names and increased hierarchical classification for those soils that are of agricultural use, and a disregard, with fewer names and hierarchies, for those that are not. The local naming of soils has been examined by Kirscht and Skorupinski (1996) with respect to these features and they conclude that three distinct groups of local soil names emerge: sandy soils (*cesa*), clay soils (*firgi*), and intermediates of these. Despite the strong agricultural elements in the local naming of soils, there is an overlap evident with some aspects of pedological description, particularly soil texture and the surface features such as colour. The names and the distinguishing features of the soil names and classes local to New Marte are shown in Table 3.1 along with an approximate USDA soil classification.

Table 3.1 Local soil names, characteristics and USDA equivalent terms (local names and translations after Kirscht and Skorupinski, 1996)

Local soil name	**Soil surface characteristics**	**Land use**	**USDA**
Clay-rich soils			
Firgi bul white firgi	white coloured surface, crusting (?), with some minor surface cracking	masakwa sorghum cultivation requires annual hoeing to prevent soil becoming (*c.f.*) karel	Ustic aquicambid
Firgi selem black firgi	dark coloured surface, large deep polygonal cracking	masakwa sorghum cultivation	Ustic aquicambid Ustert if vertisol features present
Kerel ker = solid, impenetrable	dark coloured surface, large deep polygonal cracks, resistant to wetting and remains hard	not suitable for cultivation	Ustert (?)
Bal where water puddles	a term used for topographic rather than soil differences giving rise to *firgi-bal* and *kerel-bal* terms	masakwa sorghum grown on *firgi-bal* no cropping on *karel-bal*	
Balam	an area where underground granaries (Plate 3.1) are dug with a *firgi* type soil overlying a deep (1.5 m) fine-grained sand layer	masakwa sorghum grown	
Intermediate soils			
Motusku	"soils with a mixture of sand and clay"	masakwa sorghum grown; an important land-type in years of low rainfall because surface dries earlier than *firgi* soils and early crop transplanting makes best use of available water	Various including inceptisols and cam soils
Kafe shinowu	"soils with a mixture of sand and clay" but "stickier when wet" than *motusku*	masakwa sorghum grown after weeding soil too soft to be hoed so cutlass used for weeding	
Kafe kumbu	hard surface crust, no cracking evident	hydrophytic grasses	
Kare	hard surface crust, no cracking evident	no plants grow, used for threshing cereals	
Sandy soils			
Cesa kutulusku cesa = sand	fine grain sand surface which is distinctively soft	rotation of long bush-fallow period, then beans or groundnuts followed by millet	Ustept
Cesa bul white sand	coarse grain sands with harder surface than *cesa kutulusku* inducing surface runoff of rainwater	rainfed sorghum or millet with intercropped beans	Ustic cambid

3.2 METHODS - PHYSICAL CHARACTERISTICS

A series of physical measurements have been made in order to investigate the inherited differences (*i.e.* soil texture) and the manifestation of these inherited differences (*i.e.* structural parameters) between the four sites of the chronosequence.

3.2.1 Particle size analysis (Soil Texture)

The particle size distributions of samples from the soil profiles have been measured and textural assessments have been made using SSEW/MIT size classifications (Baver *et al.*, 1972). From field assessment (section 2.5), there is an obvious dominant clay texture of the surface horizons for several of the soils, therefore the quantity of fine-clay (<0.2 μm e.s.d.) as a fraction of the clay fraction (<2.0 μm e.s.d.) is a parameter that may indicate relative differences in weathering, with an increase in the fine-clay:clay ratio suggesting increased weathering. In order to measure the fine-clay fraction, particle size analysis was undertaken using an X-ray "Sedigraph" machine (SediGraph 6000e, Micromeritics Inc.,). A standard pre-treatment of 20 minutes ultrasound dispersion was used for all samples. The SediGraph machine operates using Stokes' Law (Stokes, 1851; widely restated *e.g.* Hillel, 1982), and, as such, the measurements made are comparable to either the pipette method (Robinson, 1922) or the Bouyoucos hydrometer (Bouyoucos, 1927) method. The SediGraph records a continuous particle size distribution between 70 μm (upper-limit of the silt fraction 63 μm) and 0.25 μm e.s.d. which is extrapolated to 0.20 μm e.s.d., the upper-limit of the fine clay fraction.

The SediGraph measures particle size by a sedimentation method involving gravity-induced travel rates of different size particles in a liquid with known properties as described by Stokes' Law. The largest particles fall fastest, while the smallest particles fall slowest, until all have settled and the liquid is clear. Since different particles rarely exhibit a uniform shape, each particle size is reported as an *equivalent spherical diameter* (e.s.d.), the diameter of a sphere of the same material with the same hydrodynamic properties and gravitational speed.

Sedimentation rate is measured using a finely collimated beam of low energy X-rays which pass through the sample cell to a detector. Since the particles in the cell absorb X-rays, only a percentage of the original X-ray beam reaches the detector. These are the raw data used to determine the distribution of particle sizes in a cell containing the suspension. The X-ray source and detector assembly remain stationary, while the cell moves vertically between them. The distribution of particle mass at various points in the cell affects the number of X-ray pulses reaching the detector. This X-ray pulse count is used to derive the particle diameter distribution and the percent mass at given particle diameters. The particles analysed must be more dense and more absorptive of X-rays than the sedimentation liquid in which they are dispersed. While the system measures the particle size distribution of most inorganic powders with particle diameters in the 100 to 0.1 μm range, it actually accounts for all particles in the sample cell, even those with diameters outside the analysis range therefore the soil samples are sieved < 63μm prior to analysis.

3.2.2 Linear Extensibility of Soil Clods (Soil shrinkage)

The measurement of the linear extensibility of soils has been undertaken in order to try and to ascertain a numeric parameter for the shrink/swell characteristic expressed and seen at the surface of the soils of the chronosequence. Apart from further characterising these soils this also allows for correlations to be made between this measurement and the other structural parameters measured in greater detail at New Marte. Such correlations are discussed in later chapters of this thesis.

3.2.2.1 Background to method

The linear expansion of soil clods, particularly in clay soils, has been the subject of many investigations. This has led to the definition of a co-efficient of linear expansion (COLE). Although the definition of COLE varies slightly between authors who have worked in this field (Anderson *et al.*, 1973 *vs.* Grossman *et al.*, 1968), there is a broad consensus on the methodology involved. The method relies on the measurement of the bulk density of soil clods at different soil moisture contents. This allows for the extensibilty of the soil to be assessed - *i.e.* the amount of expansion that occurs as the moisture content increases. The method is dependent upon keeping the soil clod intact as it changes moisture content whilst drying. Various methods have been developed to establish the volume of irregular shaped soil clods at different moisture contents. One of the first attempts to do this (Stirk, 1954) used a kerosene displacement method which was revived in a much modified form by McIntyre and Loveday (1974) using a saturation technique to derive the clod volume. More recently the use of a hexane displacement method (Ross and Preeble, 1989) has been suggested as a non-destructive alternative; this method has, however, failed to be adopted as a routine technique. The most commonly reported experiments use variations on a method first described by Brasher *et al.*, (1966), where Saran resin (Dow, 1964) is used in order to keep the clod together as a single entity. The Saran resin acts as a semi-permeable barrier, allowing water vapour to pass as a clod dries but it does not permit re-wetting. Methods using a Saran resin coating are destructive since the resin cannot be readily removed from the soil clod. More recently there have been investigations conducted which have examined the relevance of the COLE measurement alongside the other information that can be generated from similar procedures. In general these have concluded that whilst COLE may be a useful characterisation when differences between field treatments have been examined, other more readily obtainable parameters have been increasingly adopted (*e.g.* McGarry and Daniells, 1987) to give clearer distinctions between treatments.

3.2.2.2 Method

The method adopted follows that of McGarry and Smith (1988) with several exceptions and amendments; these mostly relate to the peculiarities of the soils studied and the physical size of the soil clods.

Sample collection and preparation:

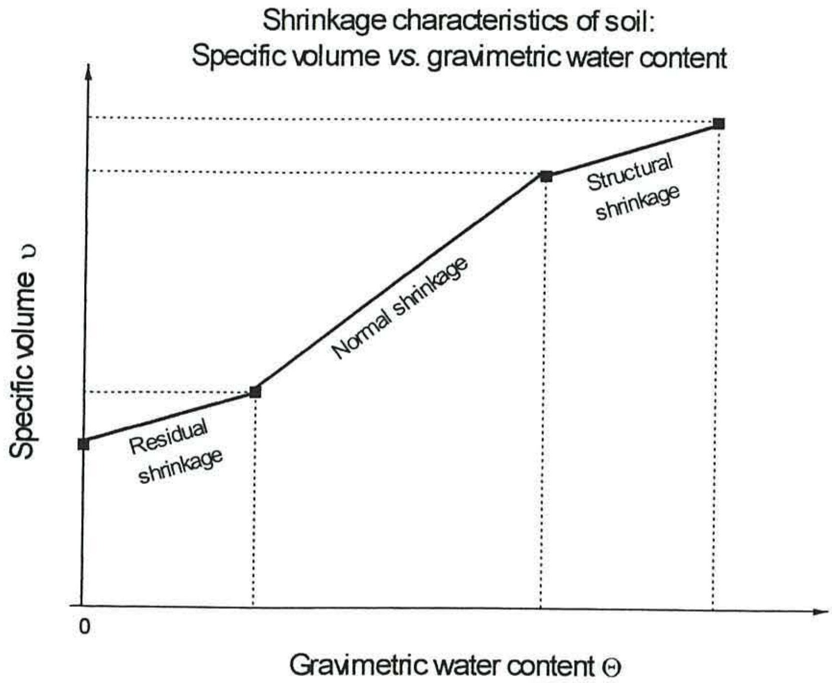
From each of the chronosequence profile locations (Baga, New Marte, Kala, and Ngeje) samples were taken of surface clods. These were either transported whole as large pieces of soil, ca. 3 kg each, or as a number of smaller pieces, ca. 200 g each, depending upon the size of the clods available and the containers available for transport and shipping at the time of sampling. Before use in this experiment, the larger pieces of soil were broken by hand along visible lines of fracture to produce clods in the weight range of 15 - 150 g.

Laboratory method:

The clods were then tied into a cradle of cotton threads and labelled using Indian ink marked tags. After weighing the clods in this air-dry state (W1) the clods were then coated in three layers of Saran resin, with a twenty minute drying period between each coating. The Saran resin was prepared as a 1:7 w/w mixture Saran resin : ethyl methyl ketone (MEK). The clods were then weighed again (W2), and reweighed after being left in air-dry (28°C) conditions for a further 48 hours (W3). This third measurement allows for checking the clods for loss of MEK solvent at this initial room temperature. At this point the first volume measurement was made by measuring the change in weight when the clod is suspended in distilled water.

Assuming that the density of water is 1.0 gcm^{-3} this gives the volume directly. The clods were then dried to constant weight at seven temperatures (35°C, 44°C, 55°C, 65°C, 76°C, 90°C and 105°C) with weighing to constant weight (W4..W10) at each interval. Three glass vials were used as controls, each dipped three times in the same Saran mixture as the soil clods. These vials show losses due to the evaporation of Saran when the clods are dried at the higher temperatures.

Figure 3.1 Types of shrinkage



3.2.2.3 Data processing

The data collected were plotted: clod specific volume ν (*i.e.* reciprocal bulk density) vs. water content θ. These data produce line graphs with eight co-ordinate points for each clod. The measurements obtained were processed statistically, utilizing techniques first described by Anderson *et al.*, (1973) and used by McGarry and Daniells (1987). Several authors have used the results of clod shrinkage experiments as the starting point for a comparison of field treatments. The papers produced by McGarry (with others) over the period 1986-1990 conclude that the most important index when comparing field treatments is that at zero water content (*i.e.* specific volume of sample when dried at 105°C) (Figure 3.1). From McGarry's results, the slope of a fitted line at this point (*i.e.* residual shrinkage) also appears to be important and a least squared regression analysis of θ upon ν has been made. The slope of the regression line and its intercept have been calculated along with the standard deviation of these parameters.

3.2.2.4 Suggested alternative procedure for clod shrinkage experimentation

A modified experimental procedure is proposed to overcome the problem of very little shrinkage when the soils gravimetric moisture content <10%, involving the uniform wetting of soil clods before the drying and measuring procedure. Whilst it is possible to consider using a sand-table moisture tension apparatus, it is probably easier to equilibrate the clods in a series of atmospheres of known relative humidity. The relative humidities above a range of saturated salts are known. The "Rubber Book" (CRC, 1995) lists a selection of salts and their associated relative humidities at standard temperature and pressure (STP: 25°C 10^4 Pa). At other temperatures the percentage relative humidity (RH) (+/- 2%) is given by $RH = A\exp^{(B/(T+273))}$ where A and B are constants and T is the temperature in Celsius.

Compound	Relative humidity (%) at STP	A	B
$CaCl_2.6H_2O$	29	0.11	1653
$MgCl_2.6H_2O$	33	29.26	34
$Mg(NO_3)_2.6H_2O$	53	25.28	220
NaCl	75	69.20	25
$(NH_4)_2SO_4$	81	62.06	79
KCl	84	49.38	159
KNO_3	92	43.22	225

It is suggested that several of the compounds from this listing are selected to create a range of initial gravimetric moisture content values for the soil clods by equilibration with these atmospheres in a desiccator. The process of measuring their specific volume can then follow the procedure detailed above (section 3.2.2.2)

3.2.3 Aggregate stability

The stability of soil aggregates is of key importance when soils are placed under stress, either anthropogenically (*e.g.* cultivation, civil engineering) or naturally (*e.g.* rainfall). To measure aggregate stability requires both a physical simulation of these stresses and, most commonly, a wetting component, since soils are most liable to degradation in the wet state (Agricultural Advisory Council, 1970). Most tests of aggregate stability have therefore assessed resistance to a combination of mechanical disturbance and wetting. However, counter to the general intuitive viewpoint that soil aggregates experiencing a rapid wetting are broken down irrevocably, Grant and Dexter (1989) and McKenzie and Dexter (1985) have reported that rapid wetting of certain compacted and puddled clay-textured soils can re-generate aggregates through micro-cracking. In addition, the vulnerability of the soil aggregates to other environmental factors, such as wind erosion, can and has been tested (*e.g.* Chepil, 1958).

3.2.3.1 Aggregate stability methodology

There appear to be two established methodologies for addressing the measurement of aggregate stability; either by simulated rainfall impact or by wet-sieving techniques. The former may be either be a "drop method", subjecting individual aggregates to a bombardment of water drops (McCalla, 1945, DeMeester and Jungerius, 1978), or a simulation of rainfall on soil in the field (Amerman *et al.*, 1970). The logistical and physical difficulties of simulating rainfall events *in situ* under trees rendered this method impractical for the current experimental study. Also, at the time of collection of these samples, there was no clear indication of the scale and levels of heterogeneity that might be present at the level of individual peds. Therefore a wet-sieving method, rather than a "drop method", was selected.

The wet-sieving technique places a representative sample of soil upon the uppermost of a set of graduated sieves which are immersed in water and oscillated vertically, simulating rainfall and flooding. This method of wet-sieving places two stresses upon the soil aggregates. Firstly there is the compression and explosion of the trapped air within the aggregate as the wetting front advances through the aggregate. This is a process known as *slaking*. If the rainfall event which is being mimicked is of low intensity then a period of gentle pre-wetting may be considered to try to avoid slaking. Emerson (1954), first demonstrated the effect of the initial rate of wetting upon aggregate strength. In the instances where aggregate breakdown of the vertisolic soils under consideration may restrict subsequent infiltration, the rainfall intensity is assumed to be high. During the 1993 rainy season the initial (mean for first hour) rainfall intensity of rainfall events recorded at the New Marte site had a range from 0.2 mm/hr to 26.9 mm/hr with the majority of large-scale rainfall events having high initial values of rainfall intensity. For comparison, in temperate areas the initial rainfall intensity rarely exceeds 2.0 mm/hr (Natural Environmental Research Council, 1975). Therefore a rapid wetting procedure seems most appropriate in these circumstances. The rate of wetting has been found to be a key factor in aggregate strength measurements, Dickson (1991) reported that clay soils had lower aggregate stabilities than medium textured soils (all air-dried) when exposed to rapid wetting rather than wetting by capillary action.

The second stress imposed upon the soil aggregates during the wet-sieving procedure is that of abrasion created by the aggregates brushing against one another as the sieves oscillate. The frequency of the sieve oscillation is the determining factor of this variable, therefore a range in the length of time of sieving rather than the number of oscillations has been adopted (30 seconds to 10 minutes) using apparatus geared to produce a fixed oscillation frequency.

The handling and storage of the samples prior to measurement has been kept consistent for all the samples measured. This is particularly important in respect of the differences that can occur due to drying, either naturally, or artificially in a laboratory oven. It has been reported that the precipitation of naturally occurring binding agents at strategic inter-particle positions may increase solid-phase cohesion of the aggregated material when the soil sample is dried (Kemper and Rosenau, 1986; Bullock *et al.*, 1985). Overall the effects of the water content of the initial material seem to have as much a bearing on this type of analysis as that of biological or physico-chemical factors.

3.2.3.2 Apparatus design

A variety of apparatus has been created for wet-sieving measurements, with an original design by Yoder (1936) spawning many similar apparatus. This lack of uniformity has been addressed by several authors calling for a standardised procedure to be created, usually simultaneously with their own standard (*e.g.* Kemper and Koch, 1966; Kemper and Rosenau, 1986; Elliot, 1986). Several specialised interest groups have created their own standards, (*e.g.* British Geomorphological Society - Grieve, 1979); however, there is still no internationally recognised methodology (Beare and Bruce, 1993). In this instance, the method employed follows that of Grieve (1979) which has been employed latterly by Blackman (1992). The apparatus is shown in Plate 6.3. The 12 V electric motor takes its power supply from a suitable source. In Nigeria this was a 45 Ah car battery, whereas an ac to dc transformer was used with the apparatus for experiments in the UK. With suitable power applied, the motor is geared to achieve 20 revolutions/minute when fully loaded with sieves. The water level in the bowl is set at 6 mm above the mesh of the uppermost sieve when this is at the highest position in the oscillation. The amplitude of the oscillation is 38 mm which is less than the distance from the rim of the sieve frame to the sieve mesh (Figure 3.2), thus preventing any loss of material from the sieve.

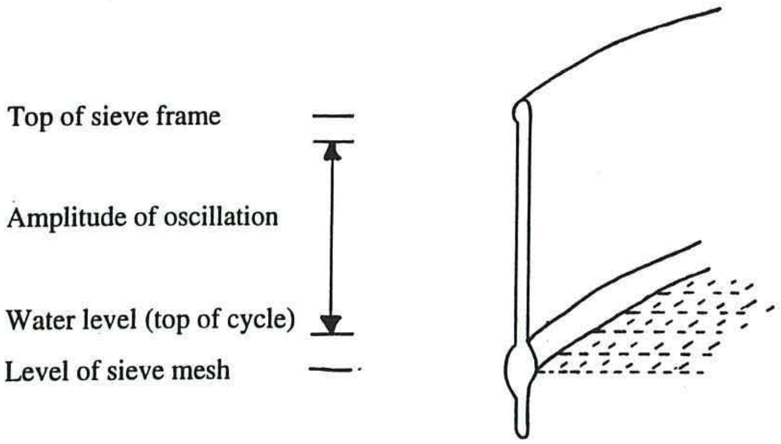


Figure 3.2 Detail of sieve position with respect to water-level

The selection of mesh size of the sieves used is a particularly contentious issue in many previously reported experiments. Some authors have stated that the use of a single sieve size is sufficient to pick up distinctions between treatments (Kemper and Koch, 1966). In their 1993 review, Beare and Bruce urge caution in accepting this argument, particularly where biological factors are of consideration. After a series of trial experiments with a range of sieve sizes from 0.3 mm to 2.0 mm mesh size, two sieves of 1.4 mm and 0.5 mm mesh were selected for the New Marte soils (Chapter 6) and for the chronosequence samples. The sieve size of 1.4 mm is used in the Grieve (1979) methodology and the 0.5 mm mesh size has been used as an arbitrary discriminative size between micro- and macro-aggregation (Oades and Waters, 1991). Sieve sizes less than 0.5 mm were rejected as they were found to clog readily when the more clay-rich soils of New Marte were used.

For each sample the larger pieces of soil were, if necessary, broken by hand along natural planes of weakness into smaller aggregates. A fraction of 2 mm - 5.6 mm was manually sieved from the bulk material. For each measurement a 100.00 g sub-sample was placed upon the uppermost sieve with all the apparatus raised out of the water. The apparatus was then gently lowered so that the sieves entered the water and the electric motor was started immediately. At the end of the period the whole apparatus is raised out of the water. The material left on each sieve after this period is transferred into a foil tray for drying. At this point any stones become evident, since the soil is disaggregated when transferred. In these particular soils, no stones (>2 mm) have been found, therefore no corrections are required in the subsequent analysis. After drying at 105°C, the foil trays and their contents were weighed to +/- 0.01g. Therefore for each sample and period of sieving, 4 measurements are made (2 replications, 2 sieve size-fractions - 0.5 mm and 1.4 mm).

3.3 CHEMICAL PROPERTIES

A range of chemical properties has been measured on selected samples taken from the soil profiles. Standard methods issued by soil science organisations and discussed by Landon (1991) have been used whenever possible.

3.3.1 Measurements

Measurements of pH and EC were made on 1:2.5 soil:water and 1:5 soil:water extracts respectively using the method described by Black (1965). Attempts were made to obtain a saturated paste extract (Landon, 1991) for the measurement of electrical conductivity, but it was not possible even with >500 g of soil to obtain sufficient extract for an EC measurement to be made.

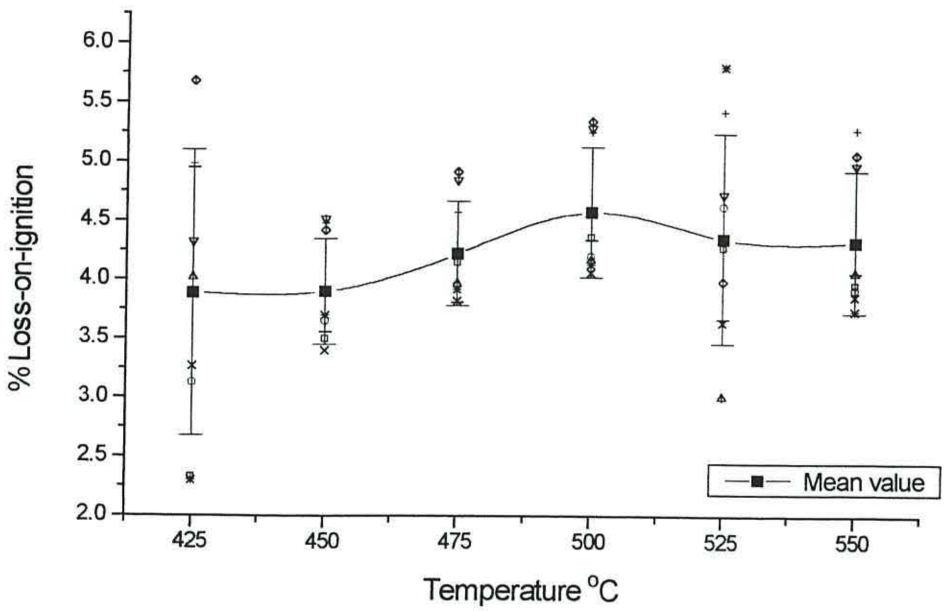
A standard Kjeldahl digestion method with a Se catalyst was used for measurement of Total N (Page *et al.*, 1982). Total P was measured by nitric acid digestion with inductively-coupled-plasma emission spectroscopy (NRM Jealott's Hill Laboratories, standard procedures). Organic C, expressed as percentage organic matter, was measured using a modified Tinsley digestion (Hesse, 1971; Page *et al.*, 1982).

3.3.2 Loss-on-ignition method

In order to select the optimum temperature for the measurement of loss-on-ignition for all of the samples analysed for this variable, a trial experiment was performed with a selected set of ten samples from both the regional profiles and site-wide (see Chapter 4) samples. These were ignited in an oxidising environment (air) for 16 hours (overnight) using a silica lined muffle furnace. The samples were then transferred to a desiccator, cooled over silica gel and measured to constant weight.

The results are plotted in Figure 3.3 with the standard deviation around the mean plotted as vertical bars. The greatest variability in the percentage loss was found at the lowest temperature 425 °C, whilst the least variability was found at 475 °C and 500 °C. The greatest average loss was found at 500 °C too. Therefore for the analysis of subsequent samples this temperature was used.

Figure 3.3 Loss-on-ignition vs. Temperature of ignition for selected samples.
(bars show sample standard deviation around mean value)



3.3.3 Calcium carbonate measurements

The calcium carbonate content of the soil profile samples was estimated using a calcimeter built to the design specified by Black (1965). This apparatus measures the volume of CO_2 evolved when carbonates such as calcium carbonate or dolomite are dissolved by hydrochloric acid.

For calcium carbonate:

$$CaCO_3\ (s) + 2\ HCl\ (aq) \rightarrow CaCl_2\ (aq) + H_2O(aq) + CO_2\ (g)$$

or for dolomite (weak reaction unless heated):

$$CaMg(CO_3)_2\ (s) + 4\ HCl\ (aq) \rightarrow CaCl_2\ (aq) + MgCl_2\ (aq) + 2\ H_2O\ (aq) + 2\ CO_2\ (g)$$

Since the method does not differentiate between the reactions of calcium carbonate and other carbonates the results are quoted as percentage calcium carbonate equivalent.

3.4 MINERALOGY

The mineralogy of the soils forming the chronosequence across North East Nigeria has been studied for two purposes. First, the composition of the heavy mineral and the clay mineral fractions may reveal further information on the soils' parentage and pedogenesis. Second, the clay mineralogy will have implications on both soil physical and chemical properties and, in turn, on soil management.

3.4.1 Background

Despite extensive literature searches, little information on the mineralogy of the soils of this region is available. The geology of the region is discussed in section 1.6. Ackroyd and Husain (1986) reviewed much of the previous mineralogical work in their examination of the engineering properties of soils found at a series of road excavations, highlighting several previous surveys. When examining the "black cotton soils" of this area, principally along an axis from the Biu plateau to Lake Chad, all surveys have reported a clay mineralogy dominated by smectites. However, Ola (1978) reported approximately 30% kaolinite as the secondary component to the smectites, whereas Clare (1957), Grainger (1951) and Lyon Associates (1971; quoted by Ackroyd and Husain, 1986) all quote or imply a much smaller (5-10%) kaolinite fraction. All authors, including Ackroyd and Husain, categorised the smectite as "montmorillonite" with no indication of either other smectite forms such as nontronite or beidellite. Also, none of these reports mention the presence of hydrous mica. The remaining major component of the clay size-fraction of these soils is quartz. The ratio between the relative amounts kaolinite and quartz give an indication of the extent of the weathering process. For the Chad Basin, the quoted ratios of kaolinite:quartz range from 0.5 to 2.5 suggesting that the weathering has ranged from relatively mild to relatively severe respectively. For a comparison to temperate climates, smectite-rich clay deposits in Britain, such as the London Beds found in Kent, have kaolinite:quartz ratios up to 5:1 (Perrin, 1971).

3.4.2 Mineralogical methodology

3.4.2.1 Sample preparation and XRDA

Using air-dried and sieved (<2 mm) soil, the clay samples were obtained after repeated dispersal in distilled water. No chemical deflocculating agents, such as sodium hexametaphosphate, were used. The samples for XRDA were prepared as sedimented slides of the total clay fraction (<2 μm e.s.d.) saturated with either KCl or $MgCl_2$. These slides were then respectively either heat treated (20 °C, 350 °C, 550 °C) or treated with ethylene glycol (EG). This procedure follows that adopted by many authors (*e.g.* Moore and Reynolds, 1989). The XRDA was performed using Philips PX1140/1138 equipment with Mn-filtered Fe K_{α} radiation at 50 kV, 40 mA, with samples scanned at 1°2θ/min. Philips PW640 series detection and counting equipment produces output on a chart recorder. The slit system employed, with Soller slits removed, was 0.1°, 1.0 mm, 0.1°. The clay mineralogy was interpreted using standard references: PDF (1963 and subsequent years) and Brindley and Brown (1980).

3.4.2.2 Examination of fine- and coarse-clay fractions

A simple qualitative method of examining differences in the mineralogy due to differences in particle size was used. The sedimented clay material on the K^{+}/20°C slide was inverted using double-sided tape, allowing comparison of the finer clay fraction against the coarser fraction of each slide.

3.4.2.3 Differentiation of chlorite and kaolinite

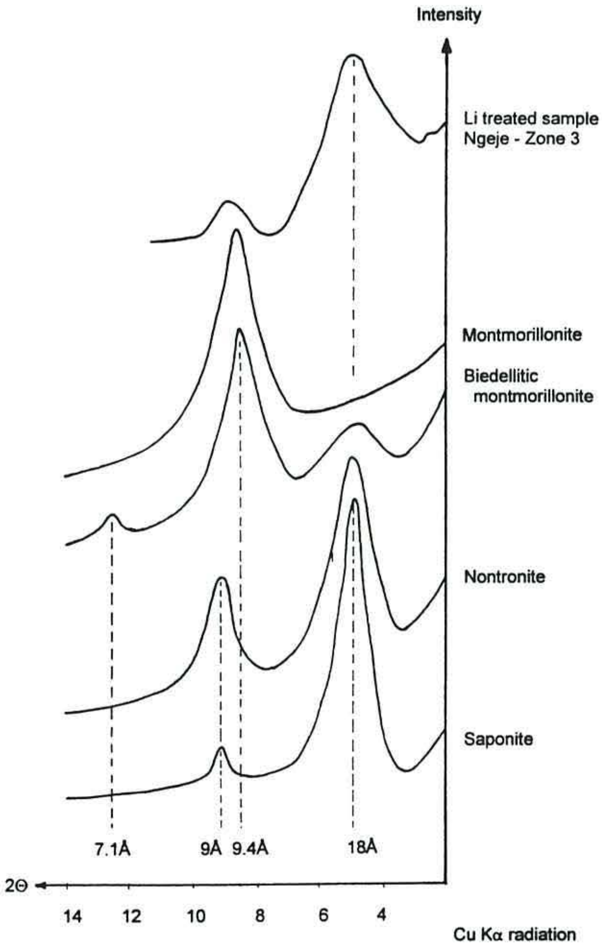
In order to differentiate between chlorite and kaolinite by XRDA, a further procedural step is involved since the method outlined above may produce ambiguous results. The method adopted follows that described by Lim *et al.*, (1981) which intercalates the clay with dimethylsulphoxide (DMSO) after pre-treatment with caesium chloride and hydrazine. This treatment selectively expands the kaolinite (by 1.12 nm) but not the chlorite, and this difference is detected in the XRDA trace.

3.4.2.4 Detailed examination of smectitic clay fraction - methodology

Characterising the lacustrine deposits which form the parent material of the soils studied in the chronosequence, may give an insight to the formation of these clay deposits. The surface features of the soils examined (sections 2.4-2.5) in the chronosequence include distinct polygonal cracking and (small-scale) gilgai features. This gives a strong indication that a relatively large proportion of the clay fraction will be smectitic. The differentiation of the various smectitic clays has been found previously to be difficult to achieve by either solvation or cation saturation methods and many mineralogists refer to the clays of this type as "montmorillonite" (*e.g.* Ackroyd and Husain, 1986). The relative colours of the unignited and the ignited (550°C) clay samples give some indication of the total Fe^{2+}/Fe^{3+} content and thereby differentiate between montmorillonite and nontronite. The method adopted, first described by Lim and Jackson (1986), involves lithium saturation of the clay extract, heat treatment, and solvation with ethylene glycol.

Lim and Jackson's (1986) method involves first washing a small (50-100 mg) sample of clay three times with aqueous 3 M LiCl, followed by two washes with 0.01 M LiCl in 90% methanol. It was found that if only small quantities of clay were available a Mg saturated sample could be "reused", with the Mg displaced by Li by repeated washing (four times) with 3 M LiCl. The Li saturated clay slurry is then sedimented onto a glass slide and allowed to dry. The slide is heated to 250°C (16 hrs) in order to collapse the clay structures, and then solvated with glycerol (16 hrs) at 90°C. The heat treated lithium-saturated montmorillonites are resistant to this solvation step, thereby allowing them to be differentiated from other smectites by XRDA. Furthermore, by XRDA, differentiation between other smectites, principally biedellite and nontronite, is possible (figure 3.4). Figure 3.4 also contains the trace of the XRDA of the Zone 3 Ngeje sample (transcribed to Cu Kα radiation for comparison).

Figure 3.4 XRDA traces differentiating smectitic clays using LiCl - 250°C - glycerol solvation treatment (after Lim and Jackson, 1986), and Ngeje Zone 3 sample XRDA trace



3.5 AEOLIAN PARTICULATE MATERIAL

3.5.1 Introduction

Aeolian material may have an important rôle in determining the characteristics of the soils of this region. Studies on the deposition of sandy material by the Harmattan (see section 1.5.4) have been focused on the stratigraphy of sediments found in lake-bottom cores (Street-Perrott *et al.*, 1989; *ibid.*, in press), with only a small number of direct observations made on the distribution of this material (*e.g.* Møberg and Esu, 1991; McTainsh, 1984; McTainsh and Walker, 1982). In Northern Nigeria, these authors have recorded rates of deposition of sand in the range of 3-9 g cm^{-2} kyr^{-1}.

Whilst the rate of deposition is low, aeolian material appears to be a major feature of the soils at New Marte (section 2.5.2), where a variable depth of sandy material is recorded overlying clay material in profiles NM1 and NM2. Samples of material taken from the surface of profile NM1 have been characterized. The aeolian material carried on the Harmattan has been sampled to compare this with this soil-surface material.

3.5.2 Sampling method

To collect aeolian particulate samples over a field season, a series of ten particulate material traps was constructed and installed across the New Marte field site. Six were at a height of 3 m to collect the material that is being transported by the wind from long distances away. Other wind blown material, moving by the processes of surface creep and saltation was collected by four collectors, two each at heights of 1 m and 0.5 m, installed within a single plot (Plot number 3; Figure 1.20). The collectors were based on a design developed at Silsoe College (Cranfield University, Bedfordshire), the so-called "Silsoe Sand Trap" (Morgan, 1986), and were constructed from standard plastic extrusions and simple metal fabrications. Plate 3.2 shows details of the design.

3.5.3 Analysis of material collected

The particulate material collected in the sand traps was separated from any dead insects (particularly bees) caught in the traps and dried (70 °C). Since only small quantities of material were available (<3.0 g), these samples were bulked together and analysed as a whole. The mineralogy of the fine sand was assessed after fractionation

Plate 3.1 Under-ground granary dug in sand under a clay-rich soil

Plate 3.2 Sand trap design (detail)

using 1,1,2,2-tetrabromoethane. The heavy mineral assemblage, mounted in Canada Balsam, was then identified under plain polarized light and between crossed polars by optical microscopy.

3.6 MESOFAUNA

From the field observation of the soil profiles (Section 2.5) it is clear from both surface and profile observations that the turnover of organic material and physical turbation of the upper layers of the soils at New Marte and at Kala is dominated by the activity of the soil mesofauna.

Specimens of the most common species of termite were collected from profile NM 1, at both the surface of the profile and at a depth of 1.45 m. The termites found at this depth were exposed in a small, roughly ellipsoidal, "nest" *ca.* 6.5 cm maximum diameter. There were distinct vertically oriented channels *ca.* 1 cm maximum diameter running from this feature. The specimens collected were kindly identified by Dr Johanna Darlington (University of Cambridge) and were subsequently added to the termite reference collection held at the University Museum of Zoology, Cambridge.

3.7 RESULTS

3.7.1 Mesofauna samples

The termites taken from the surface of the New Marte (NM1) profile have been identified as belonging to the *Odontotermes* genera, whilst the termites found at depth on the same profile were identified as belonging to the genera *Macrotermes*. The surface debris and the *Odontotermes* termites are shown in Plate 3.3. Plate 3.4 shows the nest structure associated with the *Macrotermes* in the NM1 profile.

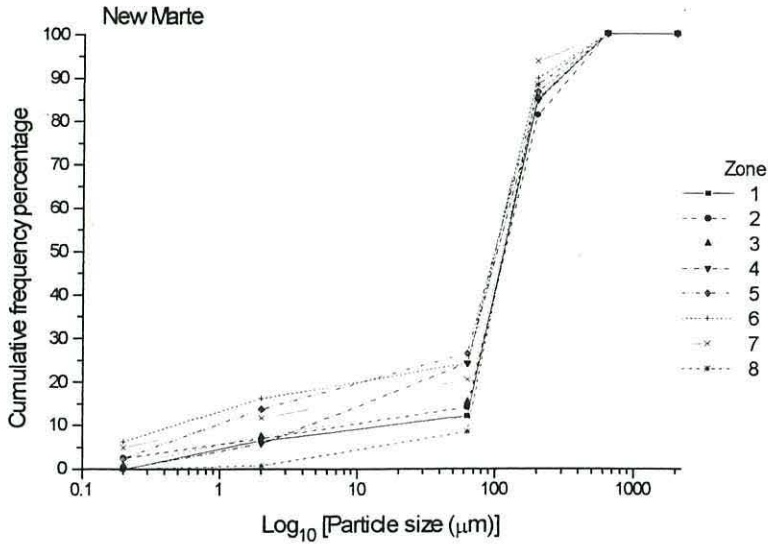
3.7.2 Chemical and physical soil measurements

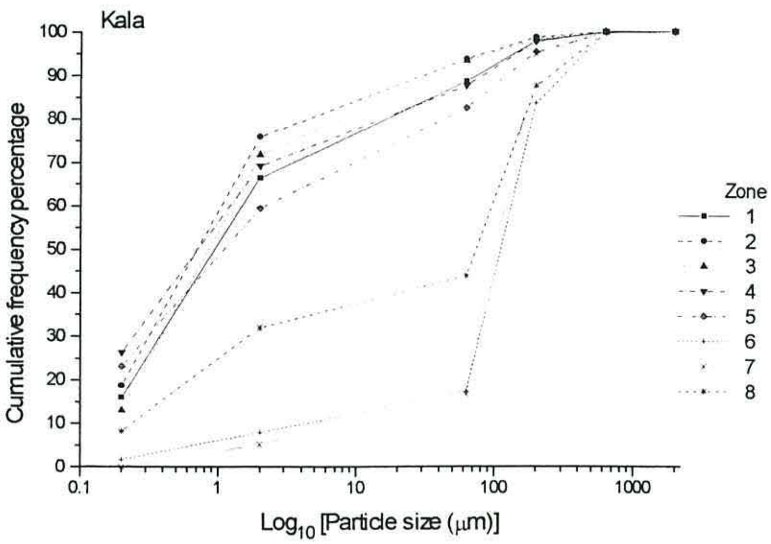
The results of the chemical analyses, aggregate stability measurements and the particle size analysis results are shown in table 3.2. Due to the loss of the Baga samples in transportation only a limited set of results for this profile is presented. To allow comparsion of the shape of the particle size distributions, these are plotted in figure 3.5 for each zone of each profile.

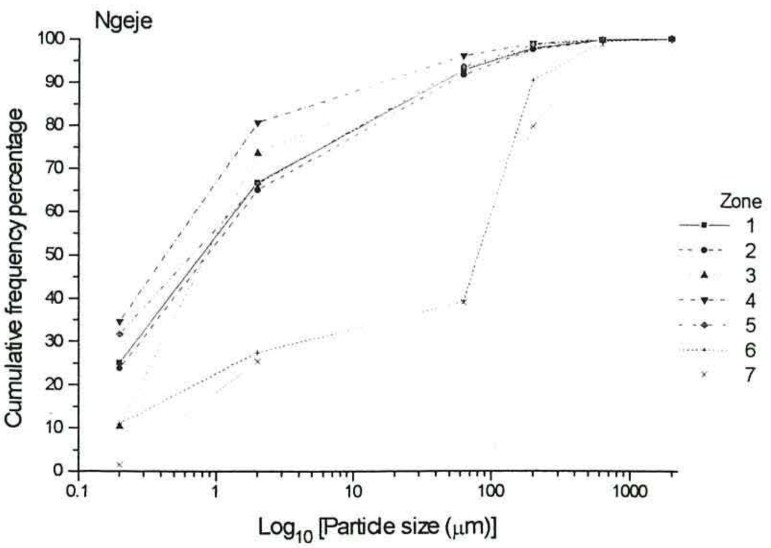
Table 3.2 Results of physical and chemical analyses - Chronosequence samples

Analysis method			Sedigraph				Sieve analysis			Wet-sieving		Chemical						
	MIT/SSEW name		fine clay	clay	silt	sand (total)	fine sand	medium sand	coarse sand	>1.4 mm after sieving for:		(- Measurement not made) (< Less than lower detection limit)						
	Size fraction (um)		<0.2	<2.0	2 to 63	>63	63 to 200	200 to 63(	>630	1 min.	10 min.	pH	EC	LOI	CaCo3	O.M.	Total N	Total P
Profile			%	%	%	%	%	%	%	%	%		mS/cm	%	%	%	%	mg/kg
	Zone	Depth (cm)																
Baga	1	0 to 8	-	-	-	-	-	-	-	15.0	0.0	-	-	-	-	-	-	-
(Baga1)	2	8 to 23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
New Marte	1	0.5 to 8	0.0	6.5	5.6	87.9	73.2	14.7	0.1	22.0	18.0	6.7	0.05	1.4	<	0.2	<	-
(NM1)	2	8 to 21	2.5	7.0	7.3	85.8	67.1	18.7	0.0	-	-	5.5	0.06	0.9	<	<	<	-
	3	21 to 30	0.9	7.5	7.8	84.7	70.2	14.5	0.0	-	-	5.9	0.05	1.3	<	<	<	-
	4	30 to 43	0.0	5.8	18.4	75.8	60.5	15.3	0.0	-	-	5.9	0.05	2.9	<	trace	<	-
	5	43 to 95	2.4	13.8	12.7	73.6	60.2	13.3	0.0	-	-	6.7	0.07	2.9	<	0.2	<	-
	6	95 to 125	6.3	16.2	8.0	75.8	65.5	10.2	0.0	-	-	7.4	0.31	2.5	trace	<	<	-
	7	123 to 170	4.9	11.7	8.8	79.5	73.2	6.3	0.0	-	-	7.7	0.23	1.7	0.01	<	<	-
	8	170 to 200+	0.0	0.8	7.8	91.5	79.8	11.7	0.0	-	-	6.8	0.11	1.0	-	<	<	-
Kala	1	0 to 2.5	16.0	66.5	22.2	11.4	9.3	2.0	0.1	26.0	5.0	6.0	-	3.3	<	0.7	0.07	148.2
	2	2.5 to 60	18.7	75.9	17.8	6.3	5.0	1.3	0.0	-	-	5.9	-	3.5	<	0.4	0.06	154.2
	3	60 to 88	13.1	71.8	21.5	6.7	4.9	1.7	0.1	-	-	6.3	-	3.6	<	0.5	0.07	171.5
	4	88 to143	26.3	69.2	18.4	12.4	10.2	2.1	0.1	-	-	6.3	-	5.7	0.10	0.3	0.07	156.9
	5	143 to149	23.1	59.4	23.1	17.6	13.0	4.4	0.3	-	-	6.4	-	4.9	<	0.2	0.07	147.6
	6	149 to153	1.7	8.0	9.4	82.7	66.3	16.4	0.0	-	-	7.0	-	0.4	<	<	0.02	16.4
	7	153 to 171	0.0	5.1	11.5	83.4	78.2	5.2	0.0	-	-	7.1	-	0.5	<	<	0.03	28.4
	8	171 to 178+	8.3	32.0	11.8	56.1	43.7	12.5	0.0	-	-	6.2	-	1.6	<	<	0.04	48.0
Ngeje	1	0 to 35	25.1	66.8	26.0	7.2	5.0	2.0	0.3	30.0	7.0	6.2	0.05	5.9	<	0.4	-	-
	2	35 to 62	23.8	65.1	26.6	8.3	5.8	2.1	0.4	-	-	6.4	0.07	5.6	<	0.4	-	-
	3	62 to 95	10.3	73.6	19.6	6.8	4.8	1.6	0.4	-	-	6.5	0.09	5.3	<	0.2	-	-
	4	95 to 150	34.6	80.7	15.4	3.9	2.8	0.9	0.2	-	-	6.5	0.10	6.1	<	0.5	-	-
	5	150 to 156	31.8	66.5	27.2	6.4	5.0	1.2	0.2	-	-	6.4	0.09	4.1	<	0.3	-	-
	6	156 to 163	11.0	27.5	11.8	60.7	51.2	8.9	0.6	-	-	7.1	0.05	0.7	0.04	<	-	-
	7	163 to 172+	1.6	25.4	13.7	60.9	40.6	19.0	1.3	-	-	6.6	0.08	1.1	<	<	-	-

Figure 3.5 Particle size distributions







3.7.3 Extensibility of soils

The results from the soil shrinkage experiment are presented in table 3.3. This includes samples from two New Marte profiles - NM1 and NM2. For all samples, the shrinkage exhibited is confined to residual shrinkage (*cf.* Figure 3.1). The table presents the slope of the least squares regression line and its intercept along with the standard deviation of these parameters.

Table 3.3 - Shrinkage parameters obtained from linear regression of specific volume *vs.* gravimetric moisture content for each profile

	Slope	SD	Intercept	SD
Baga	0.002	0.001	0.731	0.004
New Marte (NM1)	0.006	0.008	0.544	0.012
New Marte (NM2)	0.003	0.001	0.568	0.003
Kala	0.001	0.002	0.525	0.007
Ngeje	0.003	0.001	0.532	0.003

3.7.4 Mineralogy of soil samples and aeolian material

The results of the XRDA are shown in Figures 3.6 - 3.7. Additionally, heavy mineral analysis of the samples from the top (zone 1) and middle (zone 6) of profile NM1 reveals the presence of *staurolite, zircon, kyanite, sillimanite* and *garnet*. The heavy mineralogy of the aeolian material collected at New Marte is similar to this and contains *zircon, garnet, staurolite* and *kyanite*.

3.8 DISCUSSION OF RESULTS

3.8.1 Methods used

Standard methods were used for the chemical analyses and for the particle size measurements (table 3.2). This allows these and any future measurements at other sampling positions with the chronosequence to be directly compared with results obtained elsewhere (*e.g.* table 3.4 below). The other physical measurements (clod shrinkage, aggregate stability) have also used standardized methods, although they are subject to greater variations in procedure between researchers.

Figure 3.6 XRDA traces of New Marte (NM1) samples

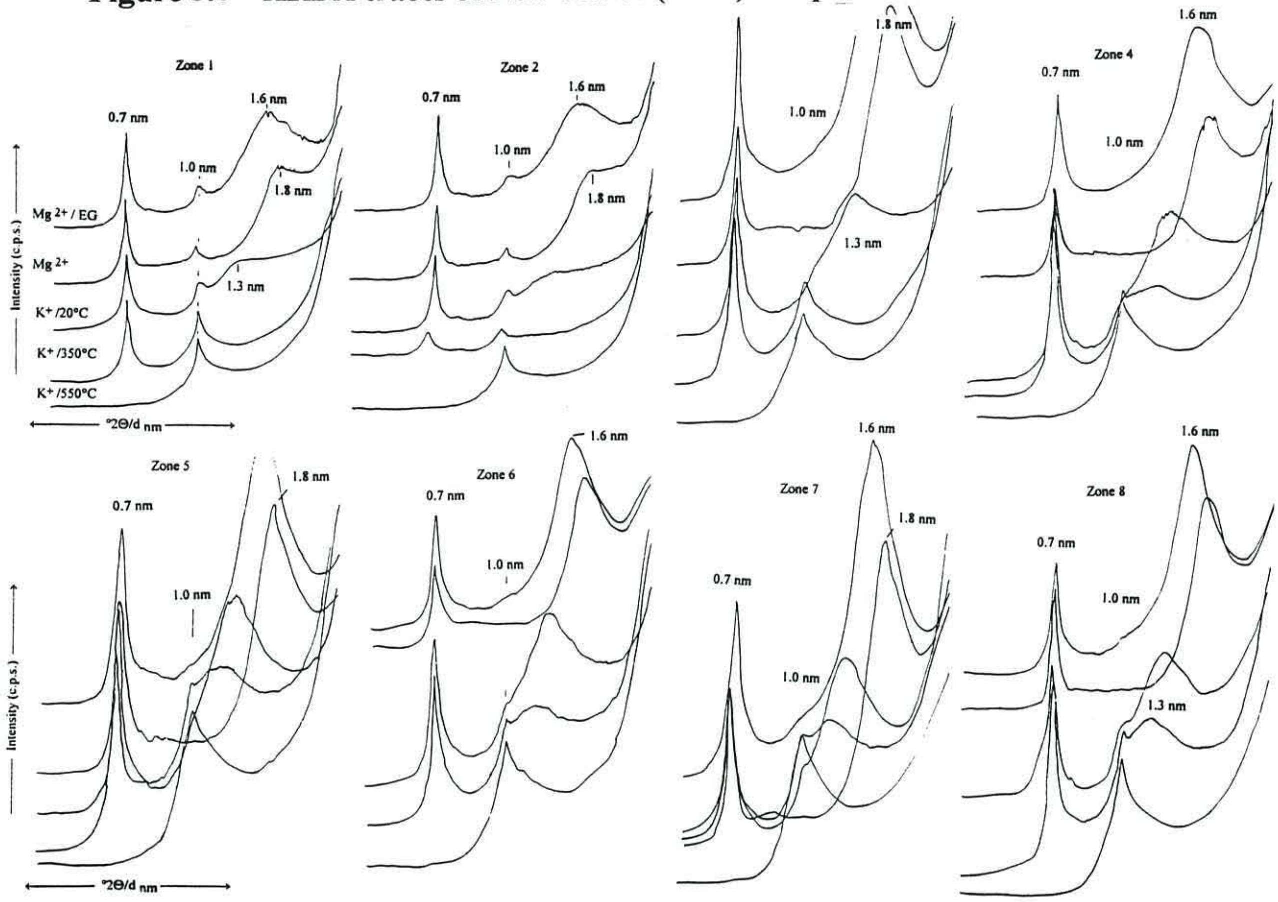
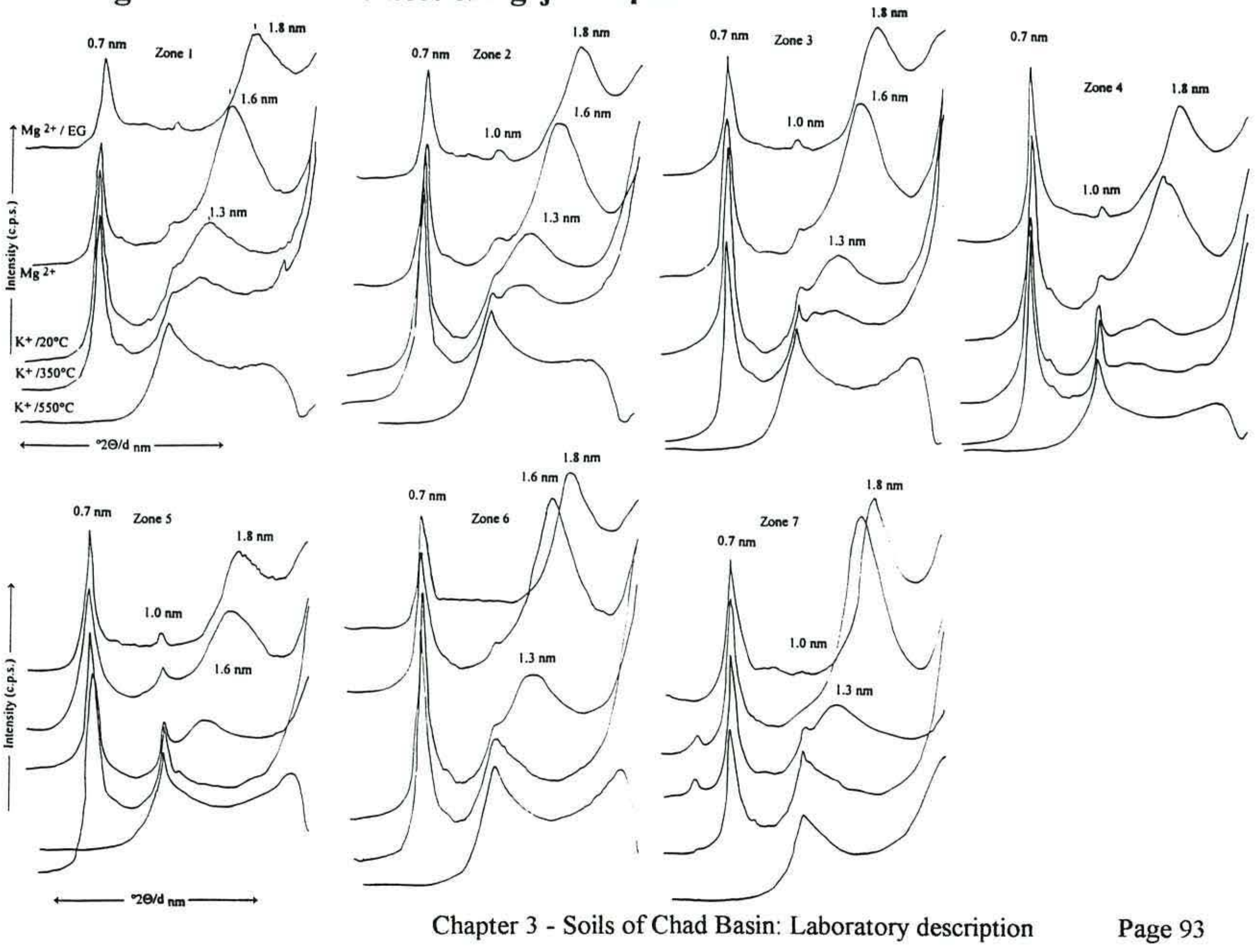


Figure 3.7 XRDA traces of Ngeje samples



3.8.2 Physical measurements

The particle size analysis reveals the New Marte profile samples to be considerably more sand-rich than the other profiles (table 3.2), with the upper zones of the Kala and Ngeje profiles the most clay-rich. The bimodal particle size distributions (figure 3.5) of the Kala zone 8 and Ngeje zone 6 and 7 material suggests that there has been a down wash of clay in these older soils. The surface horizon at New Marte shows sand deposits overlying a series of more clay-rich horizons (figure 3.5), suggesting the input of aeolian material. This contrasts with Kala and Ngeje where the input of aeolian material was not evident in this manner and the stratigraphy is clay-rich zones overlying sand layers. If the aeolian inputs to all the sites are similar then a possible explanation for this difference is that aeolian material falling onto the surface is blown into the more extensive, deeper and wider cracks at the Ngeje site, rather than remaining on the surface as at New Marte. This would further suggest that the more strongly developed soils with clay-rich surface horizons will remain with a clay-rich surface, whereas soils which do not exhibit such cracking will accumulate sandy materials on their surface. Despite the seasonal flooding at New Marte and the resultant horizontal transport processes, these differences in cracking and surface accumulation of material may influence the surface topography and accentuate surface texture differences.

The wet-sieving analyses show a larger quantity of water-stable aggregates in the New Marte samples than in the Kala or Ngeje samples although these differences are not considered significant. Since the surface conditions and the surface vegetation (section 2.3 - 2.6) vary between these sites, small differences in these factors may determine the stability of these peds. The weakly developed peds at Baga slake almost immediately which is possibly due to their chronic seasonal inundation by the waters of Lake Chad, which has a higher than rain or river-water salinity (section 2.1.1).

The results of the clod shrinkage experimentation (table 3.3) show distinctly that there is little or no change in the specific volume of the clods as they were dried from their field state *i.e.* gravimetric moisture contents of up to 10%. The method employed failed to show any differences in the type of shrinkage that these soils exhibit, and only one of the measured parameters distinguishes between the different sample locations. The results indicate that moisture contents greater than this 10% level are required to produce appreciable swelling and that an alternative method is required. A modified procedure is suggested in section 3.2.2.4..

Since there was little or no clod shrinkage at the moisture contents considered, this indicates that the field state of the soil at the time of its collection showed the maximum extent of polygonal surface cracking (Plates 2.6, 2.10, 2.14) due to the shrink/swell nature of these soils. This therefore discounts differences in moisture content on sampling as a factor in the differences in the wet-sieving measurements. The samples were kept and transported in sealed bags and containers, therefore they are not likely to have dried appreciably despite the high temperatures in which the sampling was undertaken (up to 40 °C). Whilst there is little change in the clod size as the moisture content changes during drying (figure 3.5), the intercept values differ (table 3.3) with Baga (0.73) higher than for the other profiles (0.53 - 0.57). Coughlan *et al.* (1991) attribute such differences to the initial arrangement of clay particles and their re-arrangement on drying. In this instance, the Baga soil would appear to have a more disturbed arrangement than the other profiles. Since these other three profiles show little difference, this suggests that: the maturation of the clay lake sediments is initially rapid; and thereafter the alteration and genesis of clays during pedogenesis are relatively much slower processes.

3.8.3 Chemical measurements

In table 3.2 the chemical measurements show no distinct differences between profiles. The trends that are apparent are down profiles with the differences in texture, principally clay-content, reflected in the loss-on-ignition, organic C and to a lesser extent pH and EC values. As expected, samples with calcium carbonate present are associated with high pH values. All the chemical composition measurements (total N, organic C, total P and calcium carbonate content) are close to the lower limits of detection, and the soils could be considered to be nutrient poor, although values are higher in the more clay-rich samples.

To compare with the results obtained from the chronosequnce samples, FAO "world-average" values (Silanpää, 1982) and means of Beavington's analysis of two profiles at Ngala (12° 20.9' N 14° 7.75' E), at a site close to the Yedseram river, are presented in table 3.4. Silanpää does not state the depth of sampling for the soils measured, but it is assumed that they are surface samples. Therefore, mean values of the results obtained from the surface (zone 1 samples) of the analysed profiles (Table 3.2) are presented for comparison.

Table 3.4 Measurements of "world-wide" Cambisol and Vertisol samples (from Silanpää, 1982), Ngala soils (Beavington, 1978), and mean values of all surface horizons from table 3.2

Source	Silanpää (1982)				Beavington (1978)		Chronosequence	
Soils	Cambisols (n=246)		Vertisols (n=135)		Mean of Ngala profiles - surface (n=2)		Mean of Zone 1 analyses (n=3)	
measurement	**mean**	**SD**	**mean**	**SD**	**mean**	**SD**	**mean**	**SD**
pH (* = $CaCl_2$)	6.41*	1.27	7.16*	0.72	8.0	0.1	6.3	0.36
EC ($\mu S\ cm^{-1}$)	180	100	280	530	250	100	50	0
% Calcium carbonate equiv.	2.1	5.7	8.9	12.1	0.0	0.0	< 0.05	< 0.05
% Organic carbon (Walkley-Black)	1.8	2.2	1.1	0.6	0.54	0.5	0.4	0.25
% Total N (Kjeldahl)	0.159	0.136	0.112	0.059	0.08	0.0	0.04	0.03

Although all the results obtained for the chronosequence samples (table 3.2) are generally lower, albeit similar in magnitude, to those in the world-wide samples (table 3.4), a noticeable exception is the $CaCO_3$ content values. The $CaCO_3$ content measurements are much higher in the world-wide samples which may possibly be accounted for by different parent materials. The Ngala results (Beavington, 1978) help to confirm an impression that the soils of this area are generally nutrient poor, with lower quantities of macronutrients than would be expected for vertic soils. Beavington's results also show variable (0.0 to 0.5 %) quantities of $CaCO_3$, which may suggest that another difference between the lacustrine clay soils of the Chad Basin and other vertisolic soils is due to the relative age of these soils (<5000 years since last lake recession) with limited or slow pedogenesis occurring after a rapid deposition of the lacustrine clay-material sediments as the lake receded.

The results conform to the classification of these soils already made (section 2.6.4) from the field observations (chapter 2) and meteorological information (section 1.5) with the NM1 and NM2 profiles at New Marte classified as Ustic Aquicambids. The profiles with more strongly developed vertic structural features seen in NM3, and at Kala and Ngeje, are classified as Usterts on the basis of these visible features (Soil Survey Staff 1975, 1994).

Plate 3.3 Surface foraging ***Odontotermes sp.*** **termites (termites** ***ca.*** **5 mm long)**

Plate 3.4 "Nest" structure (55 mm diameter) created by ***Macrotermes sp.*** **termites**

3.8.4 Termite identification

The set of termite specimens obtained from the soil surface of profile NM1 were identified as *Odontotermes sp.* (Plate 3.3) and those found at depth as *Macrotermes sp.*. Both of these species of termites are considered to be surface foragers, and are associated with distinct above-ground mound structures in which they grow fungal combs (Darlington, personal communication), but in this instance and in common with much of the New Marte field site, no mounds were visible within 25 m. This suggests several possibilities: either that the particular termite species or sub-species found at New Marte do not build above-ground mounds, or that the mounds are regularly razed by the surface flooding and therefore not built to a prominent height, or that these termites are associated with colonies distant to the sampling site. If the last of these three possibilities were found to be the case, then the horizontal translocation by termites of soil and plant material over distances larger than the length (25 m) of the experimental plot boundaries would need to be considered in any future, more detailed, studies of plant-soil nutrient dynamics.

The "nest" structure (Plate 3.4) and channels described in the NM1 profile (section 2.5.2) that run vertically, appear to be created by the *Macrotermes* termites. Whilst the "nest" and the channels appear to be long-term features, it is possible that the profile pit cut across established horizontal foraging routes and that the termites re-established these with a vertical detour creating channels over the face, or just below the surface, of the profile rather than a horizontal detour around the edge of the profile pit. However it is unlikely that the features are as a result of interference in termites foraging routes whilst digging the profile, since the profile face was freshly cut before the description. Also, occasional deep (*ca.* 2 m) passages have been reported in previous excavations of *Macrotermes* mounds (Darlington, 1982). Therefore, these features must be considered to play an important part in infiltration and vertical nutrient redistribution in the soil.

3.8.5 Mineralogy

All smectitic clay minerals have a relatively low substitution of aluminium in tetrahedral sites within the clay mineral structure, but high substitution in octahedral sites is possible, reducing the interlayer charge. This reduced interlayer charge allows for greater expansion between layers than for other clay minerals, the characteristic seen in the surface cracking of the profiles sampled. The ions that may isomorphically substitute for aluminium include ferrous (iron) ions, in which case nontronite is formed. The low interlayer charge allows for ready exchange of interlayer cations, these include Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, major ionic species found in the lake water. With these ionic species present, together with the high pH and high Si solubility of the lake waters, conditions are favourable toward the genesis of smectitic minerals.

The XRDA traces reveal the major clay minerals in all soil samples to be: smectite with kaolinite, quartz, and vermiculite (Figures 3.6 - 3.7). This assessment of the clay mineralogy agrees with previous researchers (*e.g.* Ackroyd and Husain, 1986). Although using the initial diffraction traces it was not possible to differentiate between montmorillonite and nontronite, the change in the colour of the clay material on ignition (10YR 5/3 → 5 YR 5/4) would suggest a ferrous content consistent with a nontronitic smectite. This was confirmed by the LiCl analysis (section 3.4.2.4; figure 3.4).

From the XRDA traces of the New Marte samples the <2 μm fraction of the lower clay-rich horizon (zone 6) is dominated by nontronitic minerals with minor kaolinite. The smaller proportion of smectite and the appearance of hydrous mica at the surface (zone 1) is interpreted as reflecting the influence of aeolian material, whereas this effect is diminished in the Ngeje profile. Hydrous mica is not reported in any of the previous work under taken on these soils. The dominance of a swelling smectite in the clay-rich material is consistent with the vertic characteristics manifested in pronounced surface cracking displayed by soils at New Marte, Kala and Ngeje (Plates 2.6, 2.10, 2.14) where the sand covering is absent. The inverted specimens, where the coarser clay material sedimented onto the slide is exposed, showed a relative increase in kaolinite, which is to be expected. The mineralogy described is consistent with the lacustrine parentage of this soil. Since this particular sample is very clay rich (38% <2 μm esd) it is likely to be representative of all lacustrine materials on the site. The fine-sand heavy mineralogy of both sandy and clay-rich horizons indicates a provenance ultimately derived from a metamorphic (*staurolite, kyanite, sillimanite, garnet*) and silicic igneous (*euhedral zircon*) terrain.

3.9 Conclusions

The mineralogy of these samples, as expected, conforms to the lacustrine parentage and to the results of previous researchers. In more detailed analyses, it has been shown that the smectitic clay fraction is nontronite, an iron-rich form of smectite. Also hydrous mica has been detected in the upper horizons, an indication of the aeolian inputs to these soils. Both of these results have not been noted previously. The depth (2 m) of the mesofauna channels would appear to be particularly important to infiltration and to the redistribution of materials from the surface, including aeolian material. Therefore, research into the rôle of the meso-fauna and quantification of the processes they are involved in would provide an obvious central topic for any future detailed investigations of these soils.

The physical and chemical measurements made on the samples from these chronosequence profiles conform to the USDA classifications made during the profile descriptions, with the younger soils classified as inceptisols and the more strongly developed soils as vertisols; the distinction being made on visible features. Whilst the clod-shrinkage experiment revealed relatively little information, it would appear that after the initial drying of the clay sediment, pedogenic clay features are slow to develop. An alternative method is proposed to try and overcome the difficulties encountered with the procedure and to clearly distinguish shrinkage characteristics. The chemical measurements, in common with work by previous researchers in the area, are slightly below world-wide averages for vertisol soils. Furthermore, several of the macronutrient analyses are on the limits of detection for the techniques employed. This indicates that these lacustrine derived soils are, despite being relatively clay-rich, nutrient poor. That these soils require careful management of nutrient inputs in any agricultural or forestry cropping upon them is reflected in the naming and land-use given to these soils by local farmers.

The field observations (chapter 2), indicate distinct physical differences between the four profiles, consistent with a chronosequence of exposure. However, the physical measurements of the profile samples only partially reinforce this trend, with the influence of the parent material masking any more pronounced physical or chemical trends. Whilst the influence of parent materials dominates their characteristics, the soils across the New Marte site, in terms of pedogenic changes to soil structure, would appear to be coming from a clay that rapidly matured upon initial drying, towards soils with more pronounced physical vertisolic features.

4 THE SOILS OF NEW MARTE EXPERIMENTAL SITE

This chapter discusses the series of physical and chemical analyses that have been made to provide spatial measurements of soil properties across the New Marte site. These measurements provide both a general soils description, revealing spatial variation across the site, and a baseline survey which can be used to assess any subsequent modifications resulting from agroforestry practices over longer periods of time. These spatial variations can also be related to the performance of the trees on the site. The results of the soil measurements have been analysed using a variety of statistical analyses, including principal component and spatial techniques. Similarly, soil colour is examined as an indicator of general soil conditions.

The measurements discussed in this chapter have been made at an inter-plot scale (> 25 m spacing). More detailed examination of the soils is described elsewhere in this thesis. Vertical heterogeneity is discussed in Chapters 2 and 3 and, at a smaller horizontal scale, intra-plot (1 to 25 m spacing) soil measurements are the subject of Chapter 5. Additionally, more extensive studies on soil structure and infiltration rates at the intra-plot level are reported in Chapters 6 and 7 respectively.

4.1 INTRODUCTION

The New Marte experimental field site is at the second youngest position of the soil chronosequence described in chapters 2 and 3. Whilst this position within the chronosequence lies between the most recently exposed and the older soils, the New Marte site also is situated on two other physical geographical boundaries. First, the area is situated towards the northern-most limit where staple crops such as sorghum and millet can be grown. In the immediate locality, much of the farming undertaken further north, towards Lake Chad, is heavily dependent upon water supplied by drainage into the lake rather than from rain-fed water. Second, the site lies at the western fringe of the masakwa sorghum cultivation area. West of the site there is very little masakwa grown since this area is characterised by sandy soils and dune fields. These borderline positions of the New Marte site relate respectively to the climate and to the underlying geology and geomorphology, an apparent geological fault in the basement rock influencing, through drainage characteristics, the sedimentation stratigraphies above. This appears to be the prime reason why there is a distinct difference in the surface soils; east of New Marte there are lacustrine clay deposits at the surface whereas west of New Marte the surface texture of the soils are mostly sand-rich. A factor in the selection of the location of the site was the possibility of encompassing a wide variety of the soil types seen in the region. Since the soils at New Marte are typical of a wide geographic region, any knowledge gained from the agroforestry experiment should be transferable to a wide audience of local farmers.

The soils of the whole region are classified (*e.g.* Aitchison *et al.*, 1972) as "vertisols", and recent comprehensive reviews of vertisols world-wide have been produced by Probert *et al.*, (1987) on their nature and by IBSRAM (1987) on their management and utilization. The soil profile measurements (Chapters 2, 3) have classified the soils at New Marte as Ustic Psamments rather than vertisols, but these soils at New Marte with their vertic nature are typical of a wide area across much of the southern Chad Basin.

4.1.1 Site establishment

The (30 ha) experimental site at New Marte was established in 1987 with the primary objective of evaluating agroforestry tree species for use on periodically inundated vertisolic soils, with reference to their productivity and resilience to climatic variability. The influence of soil variability on tree establishment at the site and a description of profile NM1 (section 2.5.2) is discussed in an introductory paper (Adderley *et al.*, 1997). Before any planting was undertaken, the site was weeded and harrowed (depth not known, but less than 15 cm) in the 1987/88 season. Planting of the trees then took place over the five years 1987-1991. In the first year of tree growth, intercrop sorghum was planted, where appropriate according to the experimental plan. Trees were planted at 5 m x 5 m spacing, 25 trees per plot. In order that the survival of the trees planted in each of these five years could be assessed, no replacement of failed trees was planned or attempted. In each year from 1988-1992 tree measurements (see section 4.3) were made during each dry season in the areas planted. Plates 4.1 and 4.2 show the contrast in the site between 1988 and 1993.

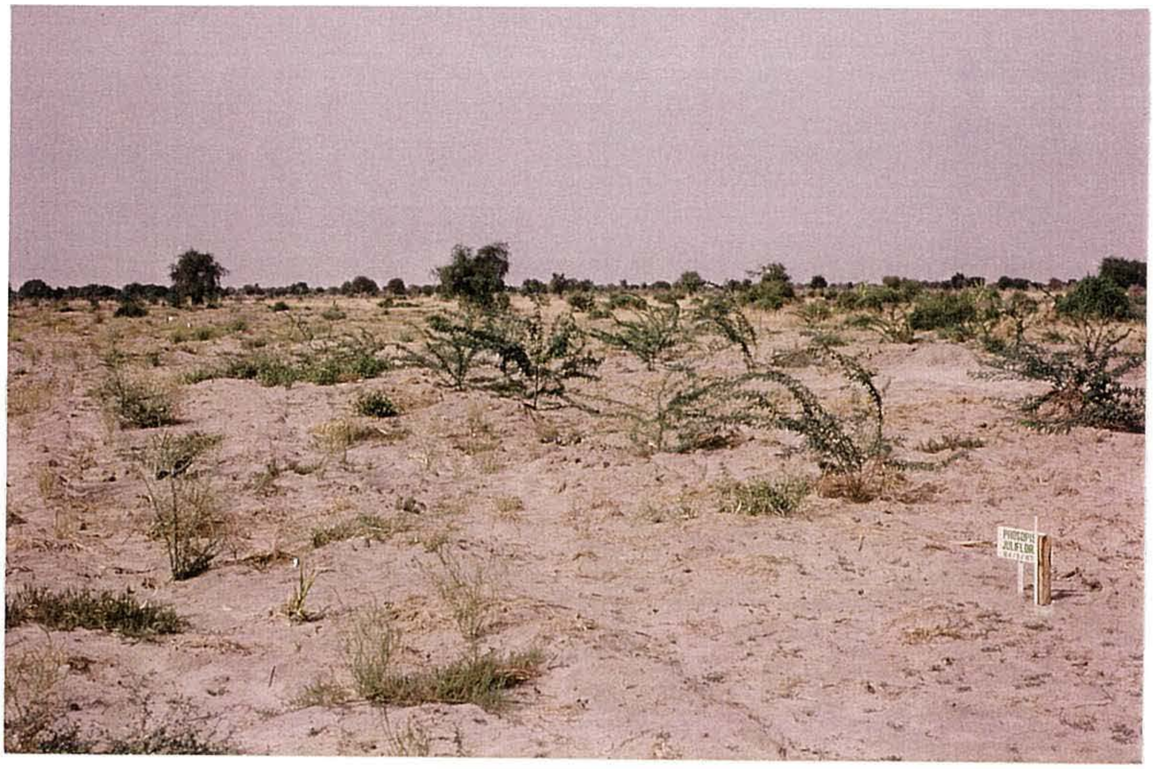


Plate 4.1 - Site in 1988. One year old *Prosopis juliflora,* showing field conditions after cultivation and planting.

Plate 4.2 - Site in 1993, showing seven year old *Prosopis juliflora*

4.2 FIELD SAMPLING SCHEMES

A series of surface (0-10 cm) soil samples (*ca.* 200g) for each plot was collected by auger. These were obtained in April 1991, with additional samples taken in May 1992. Since the sampling was designed to provide a general soils description revealing spatial variation across the site, thereby creating a base map, the samples were taken from a position in the centre of each plot, thereby avoiding the influence of tree planting or plot treatments applied to neighbouring plots.

4.3 FIELD MEASUREMENT METHODS

4.3.1 Soil measurements

Across the New Marte site there is a readily apparent change in the surface texture of the soil. This is due to a a variable layer of sandy textured material overlying the area. The depth of this surface sand, overlying clay material, was assessed across the site in the 1992/3 dry season. This was achieved by augering with a screw auger and assessing the texture until a clay texture was found. Factors such as grading of the soil particle sizes allows this measurement to be made +/- 0.05 m. The measurement assumes that the surface materials although intermixed, can be considered as a single entity; that is, this measurement represents the depth to a clay layer rather than the depth of any particular individual sandy textured layer or crusting on the soil surface.

4.3.2 Tree and site topography measurements

Since the New Marte field site was established to examine the trees in relation to a series of environmental factors, there was no beating-up of failed trees. The survival of the trees after any time period could therefore be simply counted. In the 1992 dry season the survival of the central nine trees of each plot were recorded. These values are used in the subsequent analyses. Two other important sets of site-wide data were collected by other staff working at New Marte in the 1991/2 season. Tree growth variables were measured and recorded directly for the central nine trees of each plot. These included cross-sectional area of tree stems, tree height, stem (bole) height, number of stems at specific heights and crown diameter. Additionally, the topography of the site was measured at a 25 m interval scale in 1993. This was undertaken by measuring the relative height differences between the corners of the plots across the site, determined using the difference in water levels in a hosepipe manometer.

4.4 LABORATORY MEASUREMENT METHODS

In order that the measurements obtained from these chemical and physical analyses can be used as a baseline for future measurements, the methods selected need to be readily reproducible. The methods adopted were therefore taken from standard sources *e.g.* USDA, MAFF/ADAS allowing these baseline measurements to be repeated at some future date, using either University or commercial analysis services.

4.4.1 Chemical measurements

For all of the surface soil samples (480 plots) obtained from across the site, the following parameters have been measured: stone content (% >2 mm), bulk density, air-dry and ignited colours, pH (H_2O), pH($CaCl_2$) and % loss-on-ignition (500 °C - oxidizing conditions). Investigations have been carried out on smaller numbers of selected samples in order to give greater detail to the site conditions. These include: total N (157 samples); extractable P (157 samples); organic carbon (15 samples); free $CaCO_3$ (35 samples where pH > 7.0). All chemical measurements have been made using the standard procedures of the USDA, (Black, 1965; Klute, 1986; Page *et al.*, 1982) after taking consideration of suggested alternatives in Landon (1991).

4.4.2 Physical measurements

As with the measurement of particle size on the samples taken from profiles within the chronosequence, particle size analysis was undertaken using wet sieving (>63 μm) and using a Micromeritics 5000E (X-ray) Sedigraph machine (Micromeritics Inc., Atlanta, Georgia, USA) for material <63 μm. This machine produced continuous measurements between 63 μm (upper-limit of silt fraction) and 0.25 μm e.s.d. which are extrapolated further to the upper limit of the fine-clay fraction at 0.2 μm e.s.d. (SSEW/MIT textural classification; Hodgson, 1976). No further characterisation, *i.e.* sieving at 200 μm, 630 μm, of the sand fraction was undertaken with these samples. Therefore, results of these particle size measurements are expressed as percentage sand, silt, clay and fine clay; the fine clay being a component of the clay fraction.

4.5 METHODS USED FOR STATISTICAL ANALYSIS AND PRESENTATION OF RESULTS

The results of the soil measurements need to be related to the trees planted and to each other if conclusions on the influence of the soils on the management of the site are to be drawn. Since there is a spatial element to this comparison, the soil properties, tree properties and summary variates have been presented and analysed as two-dimensional maps.

4.5.1 Presentation of results of soil analyses

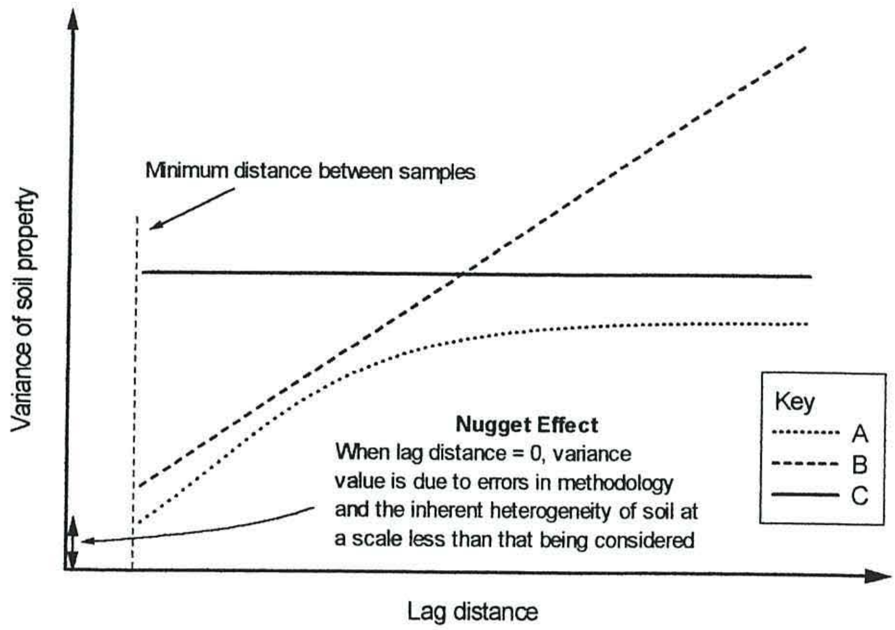
In order to detail any systematic trends or localised variation in soil properties of relevance to the agroforestry tree management, it is desirable to interpret the results in a spatial context. The measurements carried out on the soil samples have therefore been interpolated across the site to produce contour maps, using the mapping package UNIMAP (UNIRAS, 1990). The method of quadratic interpolation used ensures that discontinuities in the data across the site are recognised. Where a reduced selected set of samples has been analysed, contour maps have still been produced for these measurements. Obviously, these will have reduced resolution and are subject to greater smoothing, resulting in more diffuse boundaries. Despite their lower resolution they still provide a very accessible visual means of communicating field results and allow comparison with other mapped data.

4.5.2 Statistical methods used in analysis of soil measurements

The soil measurements made across the site have been analysed by various methods in order to relate these variables both with each other and with tree survival. After confirming normal distributions of the variables, the latent roots and vectors were extracted from a correlation of the soil variables (taking principal components), using Genstat (Payne *et al.*, 1987). A further correlation of the soil variables, together with the tree survival variable, was performed similarly. Maps of the first and second principal components have been plotted (Figure 4.12, 4.13) to provide a summary of the soil measurements. This definition of the principal component does not include spatial information; as such, this method does not impose any structure (*e.g.* linear) on the resulting spatial pattern.

In order to investigate the spatial dependence of all of these soil variables, semi-variograms (plots of the semi-variance versus the lag distance between observations following Webster and McBratney, 1987; *ibid.*, 1989; Webster and Oliver 1989) have been calculated and plotted using Base SAS and SAS/GRAPH (SAS, 1991). By visually examining the semi-variograms produced, it is possible to detect various spatial trends (Figure 4.1) using this method.

Figure 4.1: Interpretation of variograms of soil properties



Situation A: Variance increases with increasing lag distance until reaching a maximum value (*sill*) at a specific distance (*range*).‡

This implies that the soil property shows reduced heterogeneity at small lag distances, but after the limiting value is reached the property exhibits no such spatial dependence. In the context of the agroforestry experimentation, if there is any "tree effect" evident by this method of analysis, the range at which the sill is reached may be related to a physical property of the trees such as the edge of the tree canopy.

Situation B: Variance increases and continues to increase with increasing distances.

This implies a linear trend where, as the distance between sampling positions changes, the value of the soil property also continues to change *i.e.* anisotropy

Situation C: Variance does not change with increasing lag distances.

This implies that the heterogeneity of the soil property is the same at all spatial scales *i.e.* no spatial dependence.

‡ N.B. The terms *sill, range* and *nugget effect* are commonly used in discussions of spatial data analysis using variograms (*e.g.* Bailey and Gatrell, 1995).

4.5.3 Statistical analysis of tree measurements, using soil measurements as covariates

The soils data are complemented by a quantity of data from the tree measurements which have been obtained throughout the life of the agroforestry projects at New Marte (section 1.18). The tree data are of interest in the context of this thesis only for assessing the effect on the growth and establishment of trees by soil properties. In order to understand the effect of the soil properties on the trees, the soil properties have been used as a combined covariate in the analysis of several tree performance variables.

The analysis of the tree survival and establishment data presents several statistical problems. First is the need to manage a complicated experimental design and treatment structure and very large sets of data. This has necessitated the use of powerful statistical routines capable of collapsing structures within the experimental design. The statistical package Genstat (Payne *et al.*, 1987) was used for these data analyses. Second, since the site has many missing trees, there are a large number of missing values, resulting in a careful definition of the models used in the analysis. The experimental design could be analysed as if it were a balanced design if there were very few missing values for the tree measurements, using the ANOVA statement in Genstat. However because of the large numbers of missing values (*ca.* 15 %), the method of analysis employed in the ANOVA statement is not appropriate.

A general (fixed effects) linear regression model should be employed, using for example the FIT statement in Genstat. However, with this type of analysis it is difficult to find an appropriate denominator for calculating standard errors as the plot-to-plot variation is assumed to be a fixed effect. The method that has been employed specifies the problem as a mixed, random and fixed, effects model, using the REML (Restricted Maximum Likelihood) statement in Genstat. The soil parameters can be included for analysis in the mixed effects model as a series of fixed effects (*i.e.* as a covariate of the analysis) allowing their influence upon the tree performance to be assessed.

These REML analyses produce standard errors of differences (SED) between the treatment means. With the equally replicated treatments found in the design of the New Marte experiment, it is simpler to present effective standard errors for the means. These are used for comparing means at the appropriate stratum level. These are obtained thus:

A standard error of a difference is calculated by squaring the two effective standard errors (ESE), summing them, and then taking the square root, thus:

$$SED_{ij} = \sqrt{(ESE_i^2 + ESE_j^2)}$$

The approximate ESE values are calculated by:

$$ESE_i = (\Sigma_j SED_{ij} - (\Sigma_{jk} SED_{jk})/2(m-1)) / (m-2)$$

where $SED_{ii} = 0$ and m is the number of levels for the treatment.

This approximation is only appropriate if the standard errors of differences (SED values) are all estimated at the same stratum level.

4.6 RESULTS OF INTER-PLOT MEASUREMENTS

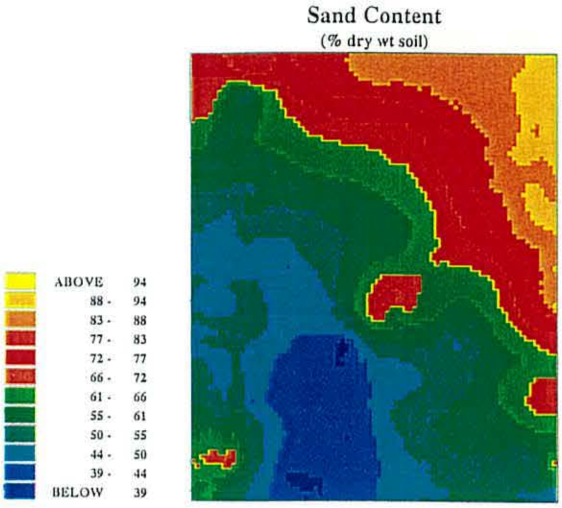
Summary information including the range and deviation of the soil parameters measured at this inter-plot level are presented in Table 4.1 whilst Appendix V contains a listing of all the raw data measurements, at all levels of experimentation, used in this thesis. In order to assess these inter-plot soils measurements in relation to each other and to basic tree performance variables, a series of different types of statistical analysis have been performed upon the results. These analyses follow the mapping of the measured soils variables.

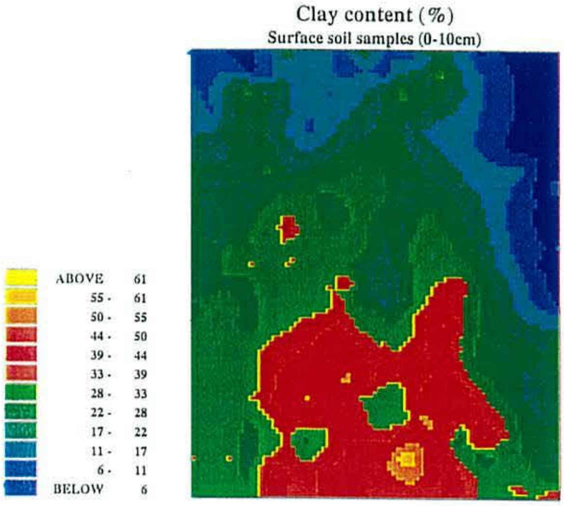
4.6.1 Mapping of soil measurements

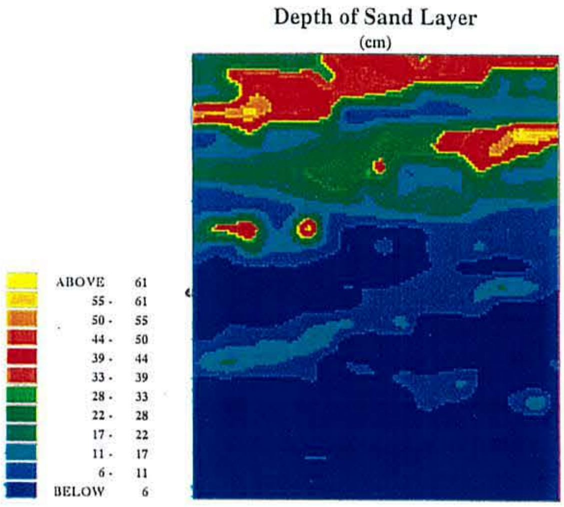
Following the method described in 4.5.1, the variation of the soil properties measured across the New Marte site are shown in a series of interpolated maps in Figures 4.2-4.11.

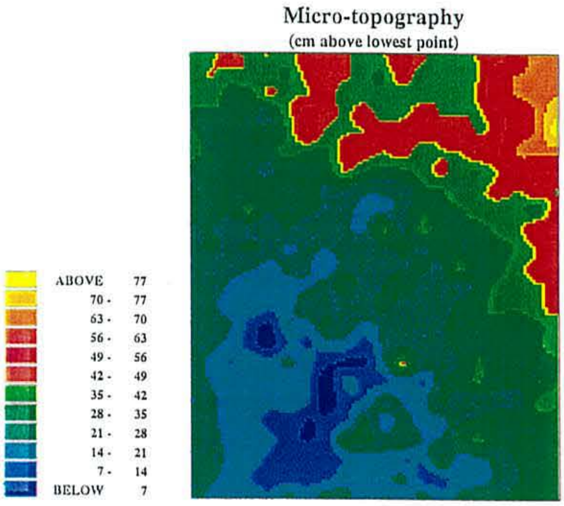
Table 4.1 Soil properties across New Marte field site

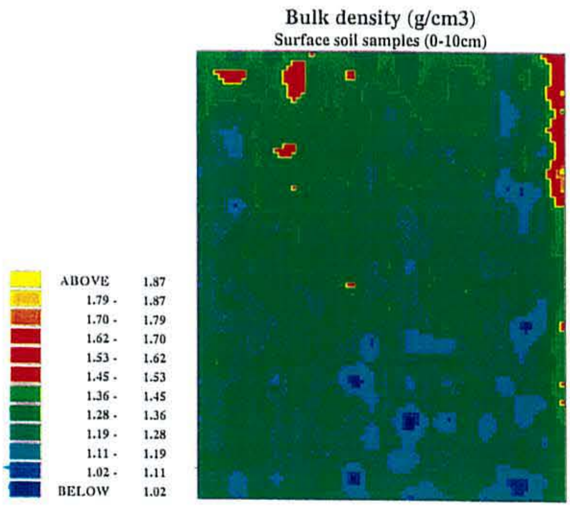
Variable	Units	Mean value	S.D.	Range	Change in variable m^{-1} Row (N-S)	Change in variable m^{-1} Column (E-W)	P wrt. tree survival	Test for significance wrt. tree survival $P<0.05$
Fine clay	%	7.0	5.3	0.0 - 35.2	0.019	0.011	0.1261	ns
Clay	%	25.8	9.1	1.7 - 62.4	0.054	0.023	0.0259	*
Silt	%	17.4	3.9	4.4 - 31.7	0.019	0.025	0.1741	ns
Sand	%	56.8	10.0	20.0 - 93.5	-0.073	-0.049	0.0180	*
Depth of sand	cm	21	13	0 - 69	-0.046	-0.016	0.6677	ns
Topographic height	cm	30	9	0 - 83	-0.047	-0.040	0.0042	*
Total N	%	0.045	0.011	0.015 - 0.107	0.000079	0.000045	0.0463	*
Extractable P	μg g-1	3.2	2.5	1.0 - 24.9	-0.0014	-0.0026	0.6169	ns
Loss-on-ignition	%	3.01	0.83	0.61 - 6.56	0.0059	0.0024	0.0001	*
Moisture content	%	1.96	0.76	0.11 - 5.04	0.0044	0.0027	0.0001	*
pH (H_20)		6.3	0.47	5.1 - 8.7	-0.0012	-0.0010	0.0742	ns
Electrical conductivity	μS cm-1	67.7	29.0	12.5 - 190	0.056	0.066	0.1241	ns
Bulk density	g cm-3	1.30	0.095	0.93 - 1.92	-0.00030	0.0000081	0.0001	*
Free $CaCO_3$	%	< 0.1	< 0.1	< 0.1 - 0.8	-	-	-	-











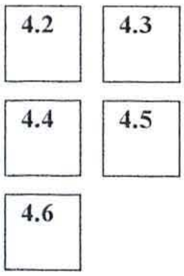
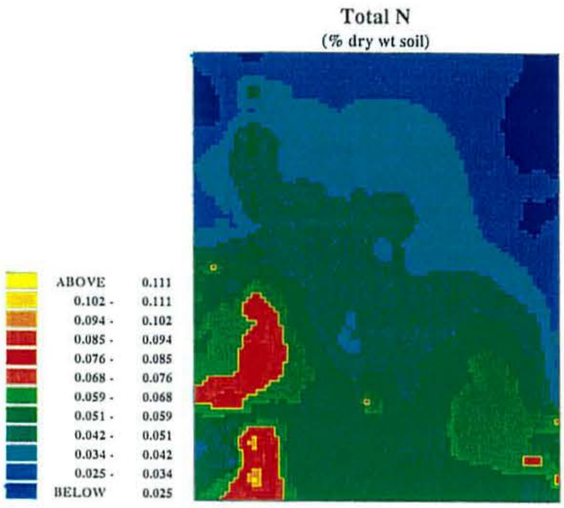
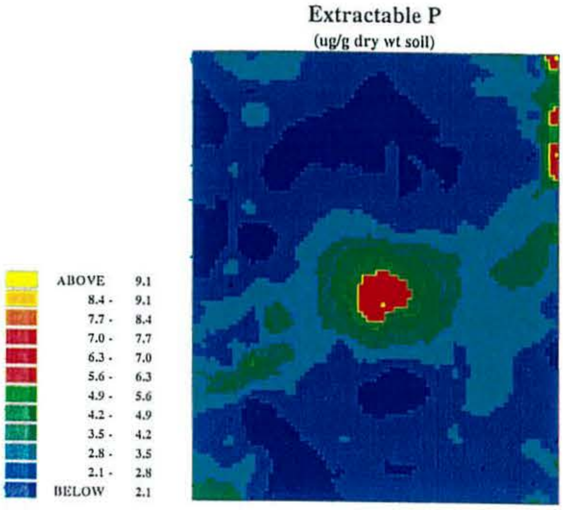
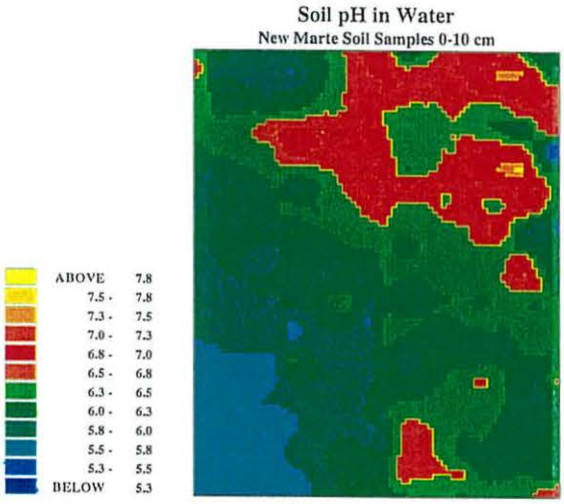
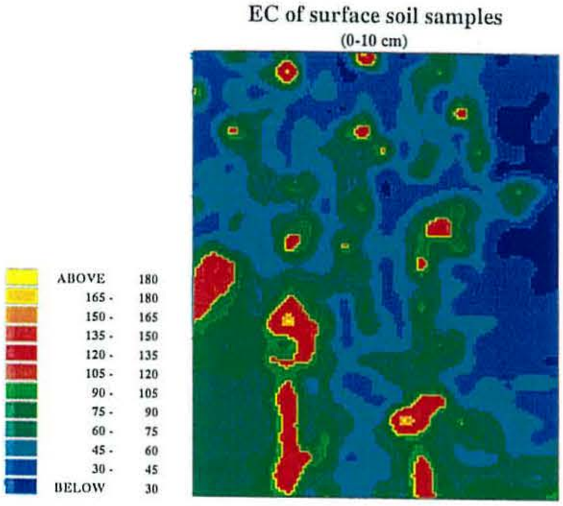


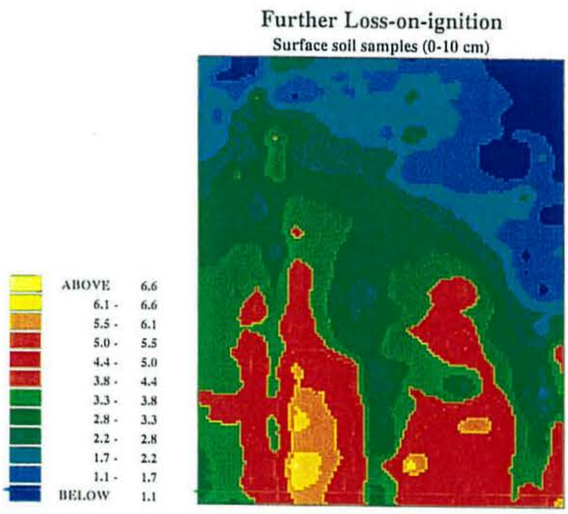
Figure 4.2 Sand content (%)
Figure 4.3 Clay content (%)
Figure 4.4 Depth of sand layer (cm)
Figure 4.5 Topographic height (cm above lowest relative position)
Figure 4.6 Bulk density (g cm^{-3})











4.7	4.8
4.9	4.10
4.11	

Figure 4.7 Total N (% dry weight soil)
Figure 4.8 Extractable Phosphorous ($\mu g\ g^{-1}$ dry weight soil)
Figure 4.9 Soil pH in water
Figure 4.10 Electrical conductivity ($\mu s\ cm^{-1}$)
Figure 4.11 Loss on Ignition (%)

Table 4.2 Correlation matrix of soil properties across New Marte site

	Fine clay	Clay	Silt	Sand	Depth sand	Topo. height	Total N	Ext.P	LoI	Moist.	Bulk density	pH water	EC water
Clay	▲▲▲												
Silt	▲	▲▲											
Sand	▼▼	▼▼▼	▼▼▼										
Depth of sand	▼	▼	▼	▼									
Topographic height	▼▼	▼▼	▼▼	▲▲▲	▲								
Total N	▲	▲	▲	▼	▼	▼							
Extractable P	ns	▼	▼	▲	ns	▲	ns						
Loss-on-ignition	▲▲	▲▲	▲	▼▼	▼	▼▼	▲	▼					
Moisture	▲	▲▲▲	▲▲	▼▼▼	▼	▼	▲	ns	▲				
Bulk density	▼	▼	▼	▲	ns	▲	▼	▲	▼	▼			
pH water	ns	ns	▲	ns	ns	▲	▼	ns	ns	ns	ns		
EC water	▲	▲	▲	▼	ns	▼	▲	ns	▲	ns	▼	▼	
Tree Survival	ns	▼	▼	▲	ns	▲	ns	▲	▼	▼	ns	ns	▼

Key

▲▲▲	very highly correlated (+ve)	r > 0.8	▲	significantly correlated (+ve)	0.7 > r > 0.46
▼▼▼	very highly correlated (-ve)	r >-0.8	▼	significantly correlated (-ve)	-0.7 < r <-0.46
▲▲	highly correlated (+ve)	0.8 > r > 0.7			
▼▼	highly correlated (-ve)	-0.8 < r <-0.7	ns	not significant P> 0.05, n=46	-0.46 < r < 0.46

4.6.2 Statistical analysis of soil measurements

In order to compare these soil analyses with one another and with other factors of interest in the agroforestry experimentation (*e.g.* tree survival), a series of statistical analyses of the soils data have been performed. These were made in an attempt to characterise any spatial trends in the soils data. The parameters measured for surface soil samples across the site are shown in Table 4.1 together with the mean rate at which the parameter changes over distance in two directions (N-S) and (E-W). Also for each parameter, a test for significance ($P<0.05$) is presented with respect to its association with tree survival.

The correlation matrix (Table 4.2) shows all of these surface soil variables along with tree survival. A test for significance at the 5% level ($P<0.05$) is implied in all of the values marked as correlated. These correlated values are further classified according to the relative strength of correlation (r).

4.6.3 Summary of soil statistical analysis

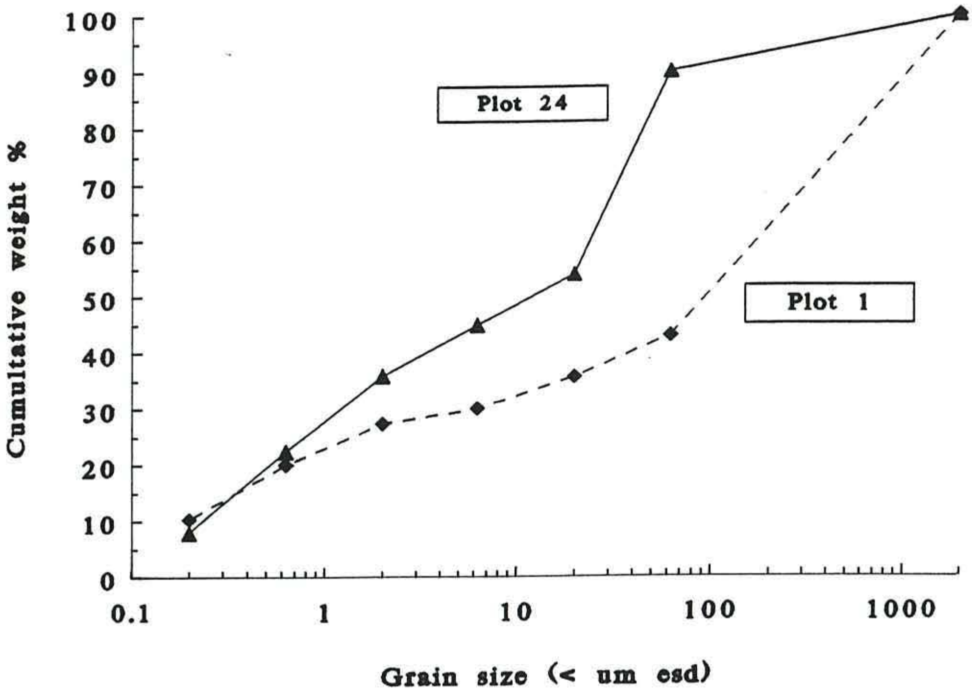
Considering first inherited properties, surface soil parameters measured across the site reveal a strong north-east to south-west polarization which is reflected in similar magnitudes of change in the (N-S) and (E-W) direction (Table 4.1). This is seen clearly in the soil texture which varies from a sandy (93.5 % > 63 μm ; Figure 4.2) to a clay extreme (62.4 % <2 μm esd; Figure 4.2) and is also reflected in the topography which slopes (*ca.* 0.1%) to the south west (Figure 4.5). These features are interpreted as lacustrine in origin. The depth of loose/friable sand cover, however, decreases to the south with a suggestion of East-West banding (Figure 4.4) with the N-S change much greater than that E-W (Table 4.1) and is presumed to be the result of aeolian deposition. Since the samples were obtained from only the top 10 cm of the soil, the change which characterises the site from a surface dominated by aeolian material to lacustrine material is clearly evident.

As expected, all these various textural and topographical parameters show strong correlations, including % fine clay (<0.2μm esd) which parallels the total clay content. By contrast, the acquired soil properties vary independently, their spatial distributions showing contrasting patterns (Figures 4.7-4.11). Bulk density (Figure 4.6) is poorly correlated with soil texture parameters (Table 4.2) with no distinction evident between the clay-rich surface soils, which are heavily cracked, and the more massive friable sand-rich soils in the north-east of the site. Soil pH (Figure 4.9) is also poorly correlated with texture showing a more irregular distribution ($P>0.05$ with % sand) which, as for the profiles (section 2.2), perhaps suggesting a variable inheritance of lacustrine calcareous material. Soil EC (1:2.5 soil:water) shows relatively weak correlation with pH ($P<0.05$, $r=-0.41$). This is also evident in their patterns of distribution (Figures 4.10 and 4.9) and their values ($5.1 < pH < 8.7$; $12.5 < EC < 190$ $\mu S\ cm^{-1}$) confirm that these soils are not saline. However, total nitrogen ($P<0.05$, $r=-0.65$, with % sand) and extractable phosphate ($P<0.05$, $r=+0.46$ with % sand) show correlations with textural parameters, the total N contents being lowest and the extractable P highest on the sandy soils. Predictably, the nitrogen content mirrors the higher organic content of the clay-rich soils, whilst the higher P content of the sandier soils relative to the clay is a little surprising, since although vertic clay soils are acknowledged to be generally deficient in P (Nye and Greenland, 1960; Moss, 1968; Russell, 1973; Katyal, *et al.*, 1987), the clays at New Marte appear to be of basaltic parentage and hence there should be a reasonable P content.

Analysis of a regression of 15 organic C values on corresponding values for loss-on-ignition showed no discernible pattern. Similarly, no significant correlation exists between the observed clay content and loss-on-ignition values although a trend is evident suggesting clay mineral dehydroxylation (see chapter 3) in the clay-rich soils to the south-west of the site. Loss-on-ignition is, therefore, not just an indicator of the clay content because where the clay content is small the relatively low organic matter content becomes more significant.

In addition to the contour map showing the parameter of % sand (63-2000 μm), a full detailed textural comparison between two extreme samples is shown in figure 4.12. Although both samples show bimodal distribution, they illustrate the distinct change from *sand* to *clay* (SSEW textural classification; Hodgson, 1976) along the eastern edge of the site. The change between the two samples is related to the mode of origin of the parent material *i.e.* either aeolian or lacustrine. This factor will have a particularly large effect on both the lateral and the vertical heterogeneity of the soil.

Figure 4.12 Cumulative curves of samples taken from NE corner of the site (Plot 1) and from the SE corner (Plot 24)

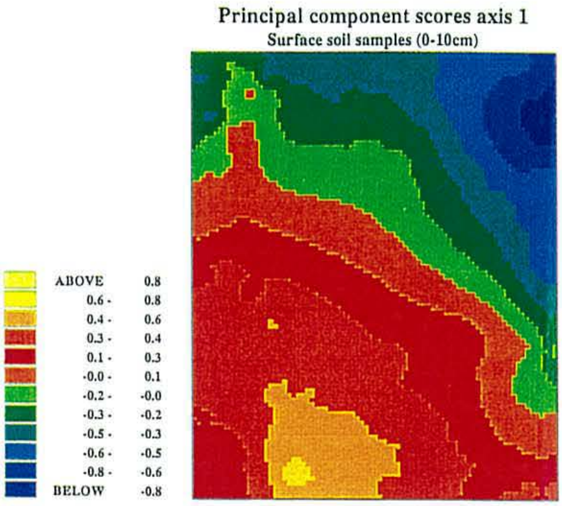


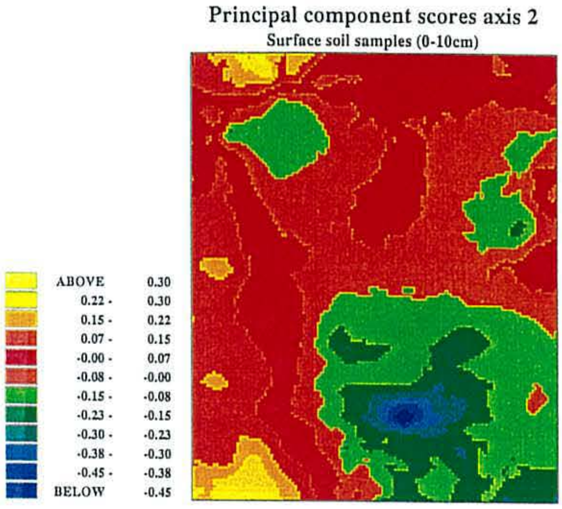
4.6.4 Principal component analysis

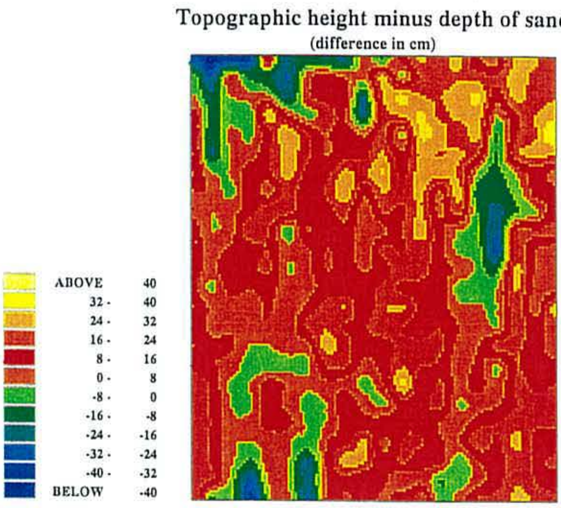
The mapping and analysis of the soil analytical results above predictably shows some indications of the dominance of inherited properties, particularly textural properties on the site. Principal component analysis is an attempt to obtain some overall parameter for the soils across the site. Using all the available coincident data (n=46) for 11 measured properties, principal components were calculated. The first component from this analysis accounts for 59% of the variation and derives in roughly equal proportions from all the textural and topographical parameters, with less from pH, EC, total nitrogen and extractable phosphate (Table 4.3). Its spatial distribution is shown in Figure 4.13 where the parallel with, and thus dominance of, soil texture is again evident. The second component of the analysis, shown in Figure 4.13, and accounting for 10% of the variation, does not show any distinct spatial trend. This is expected because a large amount of the variation has already been accounted for in the first component, again emphasising the dominance of texture, and because of the orthogonal nature of the two components.

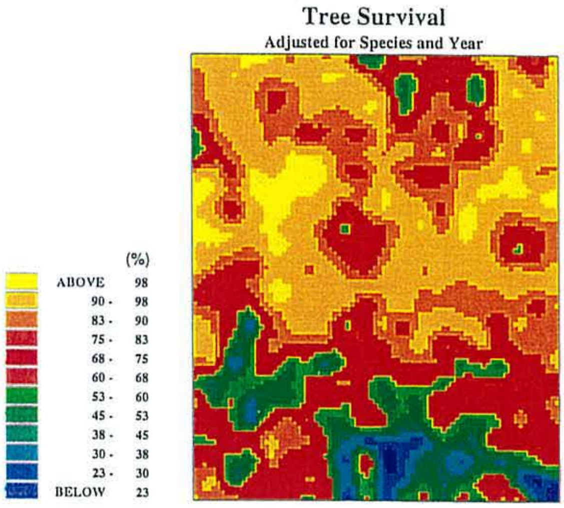
Table 4.3 Contribution of the soil variables to the first and second principal components

	Principal component 1	Principal component 2
Variation accounted for	59 %	10 %
Variable	Latent Vector (Loading)	(Loading)
Fine clay	0.28983	0.31317
Clay	0.33172	0.21793
Silt	0.31433	-0.20860
Sand	-0.34420	-0.07613
Depth of sand	-0.23225	-0.44055
Topographic height	-0.32133	0.09574
Total N	0.25791	0.00633
Extractable P	-0.16835	0.29191
Loss-on-ignition	0.29712	0.13259
Moisture content	0.27661	0.18147
pH (H_20)	-0.15063	0.54802
Electrical conductivity	0.22067	-0.25991
Bulk density	-0.23507	0.18698
Free $CaCO_3$	-	-









4.13	4.14
4.15	4.16

Figure 4.13 First PCA
Figure 4.14 Second PCA
Figure 4.15 Topographic height minus depth of sand (Δ cm)
Figure 4.16 Tree-survival (%) after removal of species and year effects - data was transformed on an angular transform scale

4.6.5 Other variables

It is possible to derive new variables from those already analysed. It has been seen that the influence of aeolian sand material on the vertical heterogeneity of the soils is particularly important (section 2.3 *et seq.*). Therefore, a derived variable has been created and mapped showing the difference between the topographic height and the depth of the friable sand layer, which should indicate the topography of the underlying clay surface. Figure 4.15 shows this derived variable and reveals very little change over the site, with few areas appearing as negative values *i.e.* topographic height less than depth of sand layer. Such areas would appear to indicate depressions or channels in the underlying clay layers. Conversely, the large areas which appear with positive values may indicate both variation in the overlying sand and in the underlying clay layers, such that no conclusion about the surface of the underlying clay layer can be made.

Comparing the spatial distribution of tree survival with soil properties is important when judging the effect of soils on trees during the trees' initial period of establishment. Figure 4.16 shows a mapping of tree survival, indicating a distinct trend from south-west to north-east *i.e.* the same direction as the textural trends in figures 4.2 and 4.3, with the greatest survival in the areas with the highest sand content. These trends are considered further using analysis of semi-variances.

4.6.6 Spatial analysis of soil measurements using semi-variograms

The trends that are seen in some of the mapping (figures 4.2 - 4.11 & 4.16) and in the data analysis table 4.1, have been examined further by including the spatial distance component in the data analysis. A series of semi-variograms have been produced and are shown in Figure 4.17, showing semi-variance versus lag distance.

The semi-variograms fall into two distinct categories. Some show an ever-increasing variance as distance between points increases (*i.e.* a spatial trend), whilst the remainder display no distinct pattern (cf. Figure 4.1). This categorisation of the semi-variograms again emphasises the distinction between the acquired soil properties (pH, EC, total N, extractable P) which have no observable spatial trends and the inherited properties (texture parameters, LOI, depth of sand, topographic height). Of the semi-variograms for the inherited properties, the most pronounced trends are seen in the depth of sand and in the topographic measurements. Apart from being a result of the greater number of samples measured, this implies that there is less heterogeneity in these variables at the 25 m sampling level used. In contrast, the bulk density measurements show no distinct trend in the semi-variogram (Figure 4.17) and the rate of change across site is distinctly different in each direction (Table 4.1).

Figure 4.17 Semi-variograms of soil properties

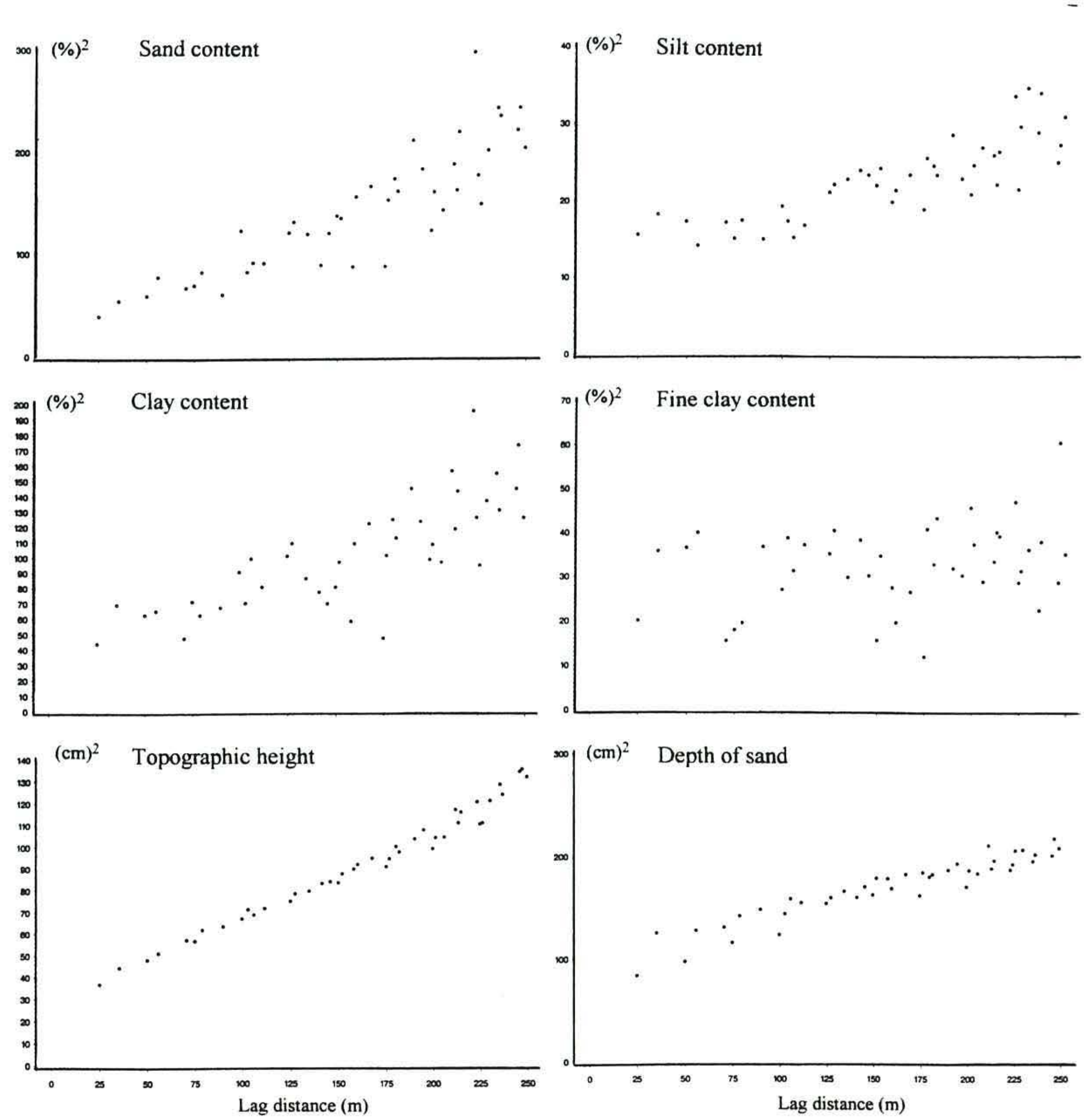
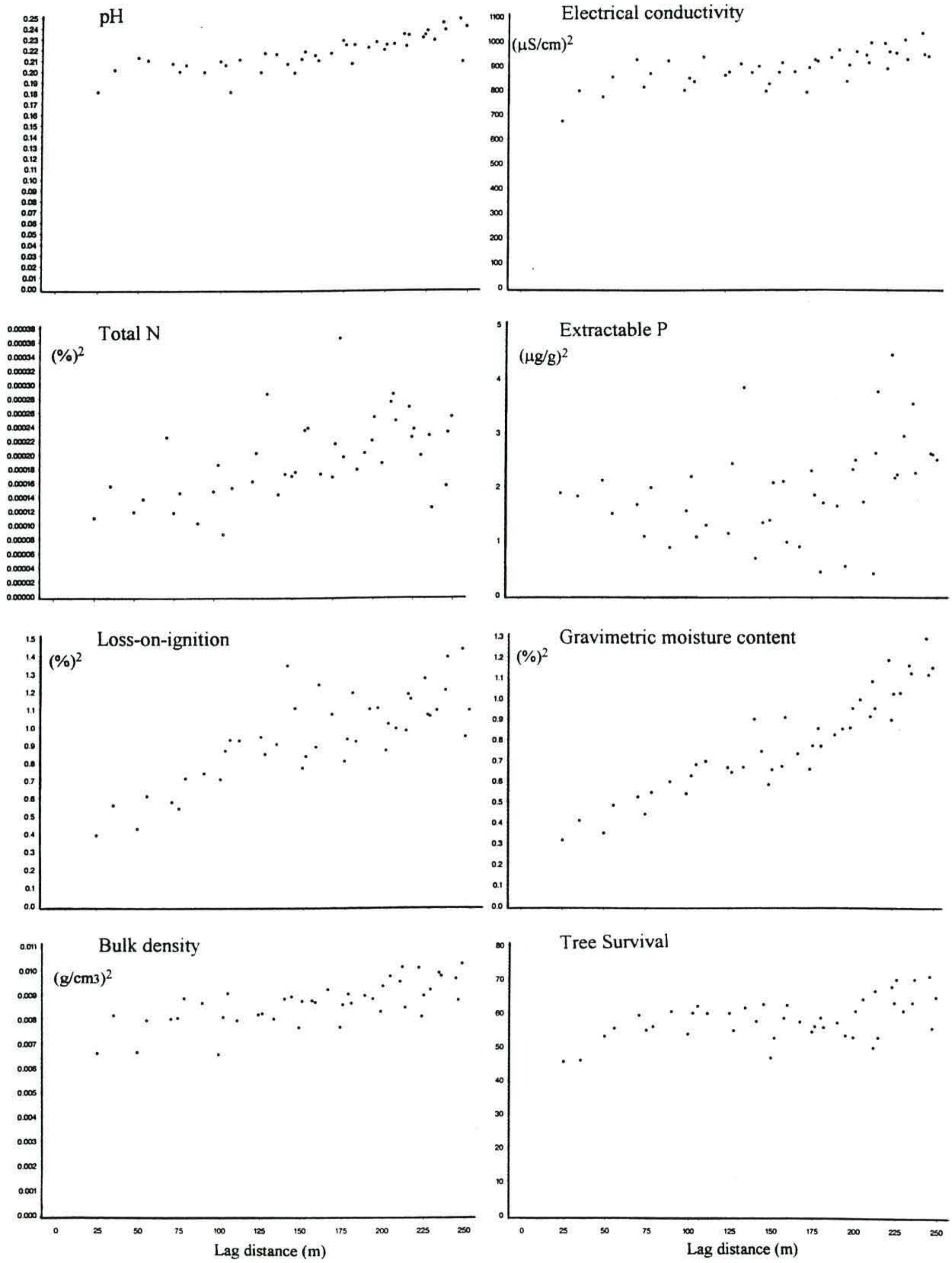


Figure 4.17 cont'd. Semi-variograms of soil properties



4.6.7 Influence of soil properties on tree performance

In order to examine the influence of soil properties on the initial performance of the trees grown across the whole New Marte site, the soil properties can be combined and used as a covariate in the statistical comparison of tree properties. These analyses also allow relative comparisons of tree species performance to be made and compare their differences between the experimental blocks of the site. For the soil factors considered in this particular set of analyses, if their influence on tree performance is not significant then other factors, such as the length of the rainy season and the anoxic conditions from the resultant flooding, must be the major factors causing the variations in tree survival seen in figure 4.16.

The most elementary observation of the trees made on the site is a record of the number of surviving trees on a plot basis. The means and effective standard errors (ese) of tree-survival of each species, for each block within the structure of the experiment are listed in Table 4.4. Species comparison within-year is made at the split-split-plot level, while year within-species is made at the main-plot level. As a result, one set of effective standard errors is shown for comparing species within year and another set of effective standard errors for comparing years within species. The tree survival values have been adjusted for species and year by substituting the species effect values and year effect values for each plot on the log scale and then transforming back to the standard scale.

The use of selected soil parameters (pH, Loss-on-ignition, Moisture content, N, P and soil colour functions) as covariates in the analysis of tree survival has produced another set of mean values and standard errors (Table 4.5) not significantly different from the initial analysis shown in Table 4.4. This is despite the parallel trends seen between sand content (Figure 4.2) and tree survival (Figure 4.16) since the particle size measurements could not be used as a covariate because of the smaller number of these measurements made. Regardless of the effect or not of the soil co-variates considered, the survival rate over the four experimental blocks varies considerably, the top two northern blocks (3 & 4) having greater survival compared to the southern blocks (1 & 2). In the southern blocks the variability in survival of any one species year on year is greater than the variability in survival between species in any one year (Table 4.4). This suggests that the survival of the trees in these southern blocks may be influenced more by site conditions during establishment (*i.e.* meteorological factors) than by species adaptation to these conditions.

Table 4.4 Tree-survival; Tables of means and effective standard errors.

Block 1.

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 1 Percent mean tree survival					
1987	94.4	81.5	80.6	69.0	76.4
1988	76.5	92.3	84.9	89.5	77.8
1989	67.6	65.2	81.4	22.7	75.6
1990	58.5	86.1	65.2	76.2	71.4
1991	69.0	55.6	31.2	33.3	69.2
Block 1 Tree survival - effective standard error between species within year					
1987	4.9	8.2	8.4	9.8	9.0
1988	9.0	5.7	7.6	6.5	8.8
1989	9.9	10.1	8.3	8.9	9.1
1990	10.5	7.4	10.1	9.0	9.6
1991	9.8	10.5	9.8	10.0	9.8
Block 1 Tree survival - effective standard error between year within species					
1987	7.1	11.9	12.1	14.2	13.0
1988	13.0	8.2	11.0	9.4	12.7
1989	14.3	14.6	11.9	12.8	13.2
1990	15.1	10.6	14.6	13.1	13.9
1991	14.2	15.2	14.2	14.5	14.2

Block 2

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 2 Percent mean tree survival					
1987	94.2	65.7	95.6	65.0	90.7
1988	76.1	79.3	83.5	49.1	57.1
1989	79.4	65.4	69.6	46.0	77.0
1990	56.0	78.1	52.9	73.3	42.9
1991	60.0	42.4	63.5	52.0	72.7
Block 2 Tree survival - effective standard error between species within year					
1987	6.0	12.2	5.2	12.2	8.7
1988	10.9	10.4	9.5	12.8	12.7
1989	10.3	12.2	11.8	12.8	10.8
1990	12.7	10.6	12.8	11.3	12.7
1991	12.5	12.6	12.3	12.8	11.4
Block 2 Tree survival - effective standard error between year within species					
1987	8.5	17.1	7.4	17.2	11.4
1988	15.4	14.6	13.4	18.0	17.9
1989	14.6	17.2	16.6	18.0	15.2
1990	17.9	14.9	18.0	16.0	17.9
1991	17.7	17.8	17.4	18.0	16.1

Table 4.4 Tree-survival: Tables of means and effective standard errors *(continued).*

Block 3

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 3 Percent mean tree survival					
1987	83.9	75.0	25.9	9.2	68.6
1988	62.1	73.3	13.1	15.4	34.7
1989	38.0	61.5	19.8	3.6	43.2
1990	58.8	59.8	24.9	31.6	24.3
1991	59.8	19.8	14.3	50.7	66.2
Block 3 Tree survival - effective standard error between species within year					
1987	9.1	10.7	10.8	7.1	11.4
1988	11.9	10.9	8.3	8.9	11.7
1989	11.9	12.0	9.8	4.6	12.2
1990	12.1	12.1	10.6	11.4	10.6
1991	12.1	9.8	8.6	12.3	11.6
Block 3 Tree survival - effective standard error between year within species					
1987	17.3	20.4	20.6	13.6	21.9
1988	22.9	20.9	15.9	17.0	22.4
1989	22.9	22.9	18.8	8.8	23.4
1990	23.2	23.1	20.4	21.9	20.2
1991	23.1	18.8	16.5	23.6	22.3

Block 4

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 4 Percent mean tree survival					
1987	67.2	63.9	1.0	3.7	44.9
1988	47.9	86.1	73.7	5.8	83.0
1989	28.6	30.7	16.7	17.2	25.7
1990	59.1	78.0	12.3	38.5	38.1
1991	72.3	64.2	40.7	3.7	60.2
Block 4 Tree survival - effective standard error between species within year					
1987	11.2	11.5	2.4	4.5	11.9
1988	11.9	8.3	10.5	5.6	9.0
1989	10.8	11.0	8.9	9.0	10.4
1990	11.7	9.9	7.8	11.6	11.6
1991	10.7	11.4	11.7	4.5	11.7
Block 4 Tree survival - effective standard error between year within species					
1987	13.5	13.8	2.9	5.4	14.3
1988	14.3	9.9	12.6	6.7	10.8
1989	13.0	13.2	10.7	10.8	12.5
1990	14.1	11.9	9.4	14.0	13.9
1991	12.8	13.8	14.1	5.4	14.1

Table 4.5 Percent mean tree survival with soil parameters as covariates

Block 1

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 1 Percent mean tree survival with soil parameters as covariates					
1987	91.2	79.9	80.6	68.6	71.0
1988	86.3	91.9	90.0	80.5	75.9
1989	74.9	65.5	83.7	24.3	80.4
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 1 Tree survival - effective standard error between species within year					
1987	2.4	2.2	2.2	2.8	2.5
1988	2.0	1.5	1.7	2.2	2.6
1989	2.5	2.8	2.1	2.7	2.1
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 1 Tree survival - effective standard error between year within species					
1987	3.2	4.4	4.3	5.1	4.9
1988	11.4	8.9	9.8	13.0	13.9
1989	14.2	15.6	12.1	14.0	13.0
1990	*	*	*	*	*
1991	*	*	*	*	*

Block 2

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 2 Percent mean tree survival with soil parameters as covariates					
1987	90.4	51.7	96.5	74.9	84.2
1988	88.4	83.9	90.2	65.4	76.6
1989	72.7	64.1	54.4	46.2	84.4
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 2 Tree survival - effective standard error between species within year					
1987	1.8	3.2	1.5	3.2	2.3
1988	2.1	2.3	2.0	3.5	2.9
1989	3.3	3.1	3.8	3.1	2.5
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 2 Tree survival - effective standard error between year within species					
1987	2.2	3.8	1.4	3.3	2.8
1988	7.4	8.6	6.9	11.5	9.8
989	10.3	11.1	11.6	11.5	8.3
1990	*	*	*	*	*
1991	*	*	*	*	*

Table 4.5 Percent mean tree survival with soil parameters as covariates *(continued)*

Block 3

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 3 Percent mean tree survival with soil parameters as covariates					
1987	79.6	82.9	20.3	21.3	71.5
1988	63.1	90.1	19.1	29.5	33.0
1989	57.7	93.9	49.8	28.4	83.7
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 3 Tree survival - effective standard error between species within year					
1987	3.2	2.8	3.0	3.4	3.3
1988	3.6	2.4	3.0	3.3	3.5
1989	3.5	2.0	3.6	3.5	2.7
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 3 Tree Survival - effective standard error between year within species					
1987	6.9	6.3	6.8	6.9	7.7
1988	24.3	15.0	19.9	22.8	23.8
1989	25.0	12.1	25.1	22.8	18.6
1990	*	*	*	*	*
1991	*	*	*	*	*

Block 4

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
Block 4 Percent mean tree survival with soil parameters as covariates					
1987	55.2	76.7	11.8	21.8	45.5
1988	68.1	95.1	88.5	16.9	92.5
1989	84.4	45.2	78.2	20.9	30.3
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 4 Tree survival - effective standard error between species within year					
1987	4.4	3.4	2.2	3.0	3.6
1988	3.4	1.9	2.3	2.7	1.8
1989	2.6	4.0	2.9	3.2	3.9
1990	*	*	*	*	*
1991	*	*	*	*	*
Block 4 Tree survival - effective standard error between year within species					
1987	4.8	3.9	3.0	3.7	4.5
1988	13.0	5.9	8.7	10.2	7.1
1989	10.2	13.8	11.3	11.0	12.6
1990	*	*	*	*	*
1991	*	*	*	*	*

The two northern blocks (3 & 4) have been used for the more detailed experimentation (Chapter 5 *et seq.*) because the greater survival of trees in these plots provides spaced trees suitably replicated for this experimentaion, whereas the southern blocks (1 & 2) do not. Several analyses were conducted (Sinclair *et al.*, 1994) to see if plots with lower survival were associated with any one specific experimental treatment. No such trend or correlation was found, suggesting that analysing the tree measurements in blocks 3 & 4 alone is a valid assessment.

The values (Table 4.6) for mean total cross sectional area of the tree at 25 cm height measurements are the back transformed values of the means on a log scale, adjusted for species and year in the same manner as the values for tree survival. The data for blocks 3 & 4 only have been considered and in this instance the effective standard errors are used to test for differences between species within each year and between years for the same species. Again, the use of the basic soil parameters as covariates to this analysis (Table 4.7) did not cause significant changes to the means and effective standard errors and both Table 4.5 and Table 4.6 show variability increasing with the age and size of the tree. However, comparing the two tables shows that the influence of soil parameters, shown by larger mean values and standard error terms in Table 4.6, is also greatest with the older plantings. This suggests that the influence of soils on tree growth, rather than on tree establishment, will become more significant over longer periods of time.

Similar to the analysis performed on the total cross sectional area, two crown volume functions, height and crown diameter, have been analysed. In the analysis of both these tree growth parameters, the use of the soil parameters as covariates yielded no significant differences. Tree height and mean crown diameter measurements across all four blocks, again after removing the species and year effects, show no discernible spatial trends suggesting that the species and age of the tree are the most significant factors in its performance.

Table 4.6 Total cross sectional area of stems

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
A) Mean total cross sectional area of stems at 25 cm height (cm^2)					
1987	61.0	31.2	29.8	4.8	79.0
1988	19.5	7.6	10.7	2.2	48.1
1989	7.6	1.6	3.7	0.7	11.4
1990	7.1	1.7	2.5	0.6	8.8
1991	0.3	0.2	0.3	0.2	0.3
B) Total cross-sectional area - effective standard error between species within year					
1987	9.7	5.0	5.5	0.9	12.8
1988	3.2	1.2	1.8	0.4	7.9
1989	1.3	0.3	0.7	0.1	2.0
1990	1.2	0.3	0.5	0.1	1.5
1991	0.1	0.1	0.1	0.1	0.1
C) Total cross-sectional area - effective standard error between year within species					
1987	11.1	5.7	6.2	1.0	14.6
1988	3.7	1.4	2.1	0.5	9.0
1989	1.5	0.3	0.8	0.2	2.2
1990	1.4	0.3	0.5	0.1	1.7
1991	0.1	0.1	0.1	0.1	0.1

Table 4.7 Mean total cross sectional area of stems with soils parameters as covariates.

Species / Year	*A. nilotica*	*A. seyal*	*A. senegal*	*Balanites aegyptiaca*	*Prosopis juliflora*
A) Mean total cross-sectional area of stems with soil parameters as covariates Blocks 3 & 4					
1987	66.5	38.9	35.2	6.8	81.0
1988	19.1	8.3	6.4	1.4	52.8
1989	6.6	1.6	4.5	0.6	15.6
1990	*	*	*	*	*
1991	*	*	*	*	*
B) Mean total cross-sectional area - effective standard error between species within year					
1987	8.8	8.1	7.2	1.3	15.9
1988	3.0	1.3	1.1	0.2	9.0
1989	1.5	0.3	0.8	0.1	3.0
1990	*	*	*	*	*
1991	*	*	*	*	*
C) Mean total cross-sectional area - effective standard error between year within species					
1987	5.3	3.5	3.4	0.6	7.4
1988	4.7	2.2	1.7	0.4	13.7
1989	1.9	0.4	1.2	0.2	4.1
1990	*	*	*	*	*
1991	*	*	*	*	*

* = missing value since analysis restricted by missing values to first three years

4.7 SOIL COLOUR MEASUREMENTS

4.7.1 Introduction to soil colour measurements

Colour is often a neglected soil measurement, despite being one of the most commonly reported attributes in most pedological descriptions. Colour has not always been reported in soil descriptions and many pedological studies prior to 1940 did not consider it as a variable (Simonson, 1993). The primary use of colour classification in profile descriptions is horizon demarcation and identification. For example, the USDA Soil Taxonomy (Soil Survey Staff, 1975) uses soil colour as a determining feature of several horizons and in turn soil classes. The USDA has extended the 1990 edition of the Munsell Soil Color Book (Munsell, 1990) in order to include colours used in their definition of Hydric soils. In this manner, soil colour is an accepted field determinant of soil type. General assumptions of the iron and manganese content and the ionic species and mineral forms of these elements can be made from colour observations (Bigham *et al.*, 1978; Schwertmann, 1993) particularly on additional ignited soil samples. In field conditions, however, such use of colour is limited due to the masking effects of organic material. Attempts made to correlate soil colour and organic matter (*e.g.* Fernandez *et al.*, 1988), have been reviewed by Schulze *et al.*, (1993) who conclude that the correlation may be poor, even in adjacent soils, if other soil factors, particularly texture, varied widely.

The integration of soil colour measurements into statistical regression analyses is rarely undertaken, even when trends between the soil colour and another measurement are indicated (*e.g.* Dobos *et al.*, 1990). This is perhaps due to a lack of understanding of colour description systems, particularly dimensional colour projections. This factor is confounded by the use for soil colour measurements of the Munsell colour system (Munsell Color Company, 1979) which uses the terms Hue, Value and Chroma. These Munsell terms are often, but incorrectly, assumed to be capable of description on linear, equi-dimensional and orthogonal axes. The Munsell system was originally devised using a series of mixing ratios of various pigmenting agents. Whilst this is particularly useful in allowing comparison with colour chips or tiles and for standardising named descriptions such as "Light brownish grey", the equivalent alphanumerical notation of 7.5YR 7/1 or 7/2 for "Light brownish grey" is not particularly useful for numerical analysis within a large data set. Specifically, the Munsell description does not readily allow for statistical analyses where there is a range of Hue terms *i.e.* where colours span more than one page in the Munsell Color

Book. To address this problem another system of colour description or a method of combining the Munsell hue, value and chroma terms is required.

4.7.2 Objective of soil colour measurements made

The large number of surface soil samples (480) has restricted the number of analyses that could sensibly be performed, particularly in view of the other objectives of the work at New Marte (section 1.8). Since there are apparent field variations in the soil texture and these are likely to influence other soil characteristics, the use of soil colour measurements, which are the easiest and cheapest attribute measured, has been examined as a possible surrogate to other soil measurements.

Given that there is a low organic content in many of the soils examined from the North East Nigeria region samples (Chapter 3), the influence of other soil attributes on soil colour may be apparent since the masking effect of the organic material is absent. Therefore, it is opportune to present a method of using soil colour in multivariate analyses of soil data sets. The New Marte site soil data provides such an example.

4.7.3 Background to colour classification and quantification

Colour classification into three-dimensional terms is a relatively recent innovation with such systems being devised from the late nineteenth century onwards. There are three related aspects of colour that such systems address. These are *hue, value* and *intensity (or chroma)* and are often described as the "dimensions of colour" (Verity, 1980). In the early twentieth century, Wilhelm Ostwald and Albert H. Munsell, working in Germany and the USA respectively, independently developed two systems describing colours in this manner. Despite being a chemist, Ostwald was interested in the aesthetic consideration of colour combinations, whereas Munsell was interested primarily in paint pigment mixtures. Whilst both of their systems are fundamentally similar, Ostwald's colour atlas was limited to the hues of pigments available at the time (1916) of its publication (Jacobsen, 1948) whereas Munsell's system was more flexible and allowed for the future development of pigments with more saturated brilliant hues. This comprehensive and flexible nature of the Munsell system made it easily adopted for technical colour descriptions. In common with many other technical users, the Munsell colour system was adopted by soil scientists.

4.7.3.1 The Munsell Colour System

The Munsell colour system is a perceptual colour space and as such it is most readily and commonly used by referral to Munsell colour charts and matching samples to the nearest matching chart entry. Thus, the major advantage of the Munsell system is its ease of use and when used in standardized conditions of illumination it has become an accepted world standard (Kelly and Judd, 1976). The Munsell system uses the terms hue, value and chroma in colour descriptions. These can be depicted on three separate axes (figure 4.18).

> *Hue* is first broadly defined as one of five single letter codes (Y - yellow, R - red, G - green, B- Blue and P- Purple) or as one of five combinations of pairs of these codes (*e.g.* YR) for intermediate hues. Each letter-coded hue is then more tightly specified by an ascribed number on a ten point scale but more usually divided into four divisions - 2.5, 5.0, 7.5, 10.0.
>
> *Value* describes the lightness of the colour and is also on a ten point scale ranging from 0/ (very dark) to 10/ (very light).
>
> *Chroma* describes the saturation of the colour and ranges between /0 - a neutral grey (or gray) of the same Value - and /14 - a highly saturated colour.

The scales of both value and chroma were each designed to be graded in perceptually equal steps, but not that the scales of these two variables be perceptually identical (Melville and Atkinson, 1985).

The main disadvantages of this system are a) that it uses pigment samples whose colours are tied to reflected light - for accurate work, therefore, controlled illumination is required; and b) since the colour space is divided into a series of non-contiguous slices (Figure 4.18) mathematical and geometric descriptions of locations within the colour space are difficult and unwieldy to use when comparing different hues.

4.7.3.2 Alternative systems of colour assessment

There are many colour description systems in use apart from the Munsell system. Mostly, these have been devised for use in specific technological areas (*e.g.*

television and computer displays - Meyer and Greenberg, 1987) and address the perceptual needs of that application. The first rationalization of colour definitions predates the electronic age and came in 1931 when a system was devised which describes any colour within a three-dimensional continuous geometric colour space. This system is known as Commission Internationale de l'Eclairage (CIE) *XYZ* system. Since this system has undergone several refinements for particular purposes, such as the textiles and dyestuff industries (CIE, 1978), this initial version is now commonly known as CIE 1931. The CIE 1931 system forms a definitive colour description with each colour described by a 3-dimensional vector, although this is often reduced to a two dimensional representation (Figure 4.19). Other, more limited, systems (*e.g.* Red-Green-Blue RGB, Hue-Lightness-Saturation HLS; Figures 4.20 & 4.21) that use a three-dimensional colour space are also vector systems. They are mainly used in colour definitions for television, computer displays and printing. These systems can be mapped by an arithmetical transformation from the CIE system. The Munsell classification, however, with its use of pigment mixing, does not use a contiguous colour space and cannot be mapped to CIE by calculation. Therefore an empirical system of comparison must be used to transform between Munsell and CIE using a known constant illuminant. An accepted standard empirical set of CIE values was obtained for Munsell colours (Newhall *et al.*, 1943), soon after the introduction of the CIE system. By using this comparison it is possible to convert Munsell values to CIE and then, if necessary convert the CIE system values to another system by calculation. This last step is necessary in order to define colours for printing on, say, a colour laser printer using RGB or HLS colour notation.

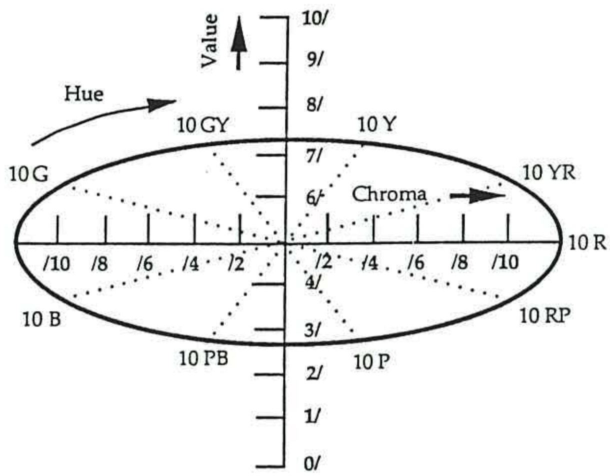


Figure 4.18
Munsell colour system

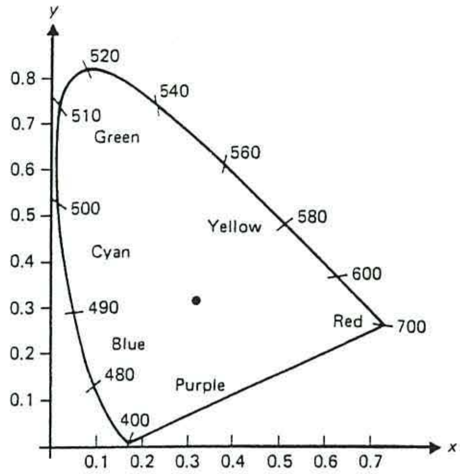


Figure 4.19
CIE 1931 colour system

Chromaticity diagram showing x and y coordinates of (x,y,Y) system. Wavelengths in nanometres

Figure 4.20 RGB colour system

Grey shades are on the dotted main diagonal

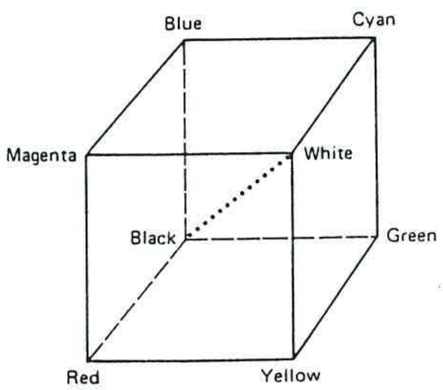
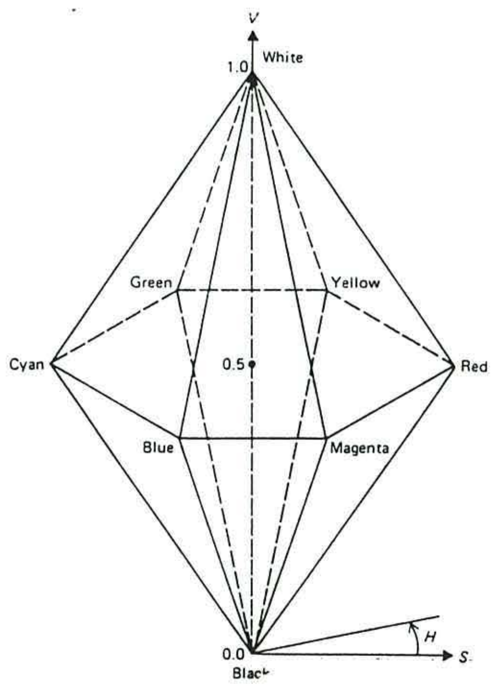


Figure 4.21 HLS colour system

HLS system plotted as a double hexcone



4.7.4 Colour measurements and analysis

The soil colour information collected on the New Marte soils was obtained by comparing the soils to Munsell soil colour charts (Munsell Color Company, 1975, *ibid.*, 1990) under the standard illumination suggested and discussed in Pendleton and Nickerson (1951), namely (for the northern hemisphere) north light on an overcast day. This illumination is considered (MacAdam, 1981) to be "very similar" to the illuminant "Standard Illuminant C" used in the measurements of CIE 1931 values made from the Munsell colour charts.

For the soils from across the New Marte site the Munsell terms for air-dry soil ranged from 10YR 5/1 to 10YR 6/3 whereas the values for ignited soil (fully oxidised at 500°C) ranged from 10YR 7/8 to 7.5YR 6/2. These Munsell measurements have been used in two ways. Firstly they have been converted, by use of a look-up table (Appendix II), to CIE 1931 terms which were then used in a multivariate statistical analysis (see section 4.7.5). Secondly a conversion from the CIE 1931 terms to HLS colour space terms was made to allow for direct mapping of these colours *i.e.* reproducing the soil colours on maps of both the New Marte site (Figures 4.22 and 4.23). The look-up table was obtained directly from Travis, (1991) which was in turn a representation of Newall *et al.*, (1943), whilst the conversion from CIE to RGB was made using a modification of a method by Travis (1991) (Appendix III). The RGB and HLS colour terms are device-specific and will differ for different colour printers. Table 4.8 contains Munsell and CIE 1931 (x,y,Y) colour space terms for the complete range of colours obtained from the 480 air-dry and ignited soil colours from the New Marte soil samples. The C computer language program used for the CIE to RGB conversion step is reproduced and annotated in Appendix III. This program contains further colour space conversions from/to RGB and HLS terms.

Apart from giving the range of colours found across the site, Table 4.8 includes a column indicating the number of samples that were found for each colour. The single ignited sample (7.5YR 6/2) is possibly an erroneous measurement (most likely incomplete oxidation), since all the other ignited samples have chroma measurements of either 6 or 8 (chroma 7 is not included in the Munsell Soil Color Book; Munsell, 1990). Both the ignited and the air-dry soil colours are clustered over a small number of value and chroma terms although the ignited soils span two distinct hues 7.5 YR and 10 YR. The changes in *value* on ignition are presumably due to oxidation of the organic material and oxidation of iron (Fe^{2+}) containing clay minerals particularly smectites such as nontronite. The CIE colour terms in Table 4.8 have also been used to create the colour plots in Figures 4.22 and 4.23 (Appendix III for further programming details), respectively showing mapping of the air-dry and ignited soil colours.

Table 4.8 Air-dry and ignited soil colour data
Colour space conversion from Travis (1991).

Munsell name	Munsell term	CIE 1931 term (x,y,Y)			No. of samples
Air-dry soil samples					
Brownish grey	10 YR 5/1	0.3546	0.3514	0.1977	26
Greyish yellow brown	10 YR 5/2	0.3546	0.3514	0.1977	55
Dull yellowish brown	10 YR 5/3	0.3995	0.3840	0.1977	5
Brownish grey	10 YR 6/1	0.3491	0.3483	0.3005	67
Greyish yellow brown	10 YR 6/2	0.3491	0.3483	0.3005	83
Dull yellow orange	10 YR 6/3	0.3861	0.3767	0.3005	47
Ignited soil samples					
Bright brown	7.5 YR 5/6	0.4440	0.3954	0.1977	63
Bright brown	7.5 YR 5/8	0.4820	0.4141	0.1977	59
Greyish brown	7.5 YR 6/2	0.3487	0.3421	0.3005	1
Orange	7.5 YR 6/6	0.4242	0.3876	0.3005	41
Orange	7.5 YR 6/8	0.4596	0.4064	0.3005	36
Yellowish brown	10 YR 5/6	0.4428	0.4338	0.1977	15
Yellowish brown	10 YR 5/8	0.4770	0.4128	0.1977	52
Bright yellowish brown	10 YR 6/8	0.4570	0.4249	0.3005	11
Bright yellowish brown	10 YR 7/6	0.4102	0.3960	0.4306	1
Yellow orange	10 YR 7/8	0.4399	0.4164	0.4306	4

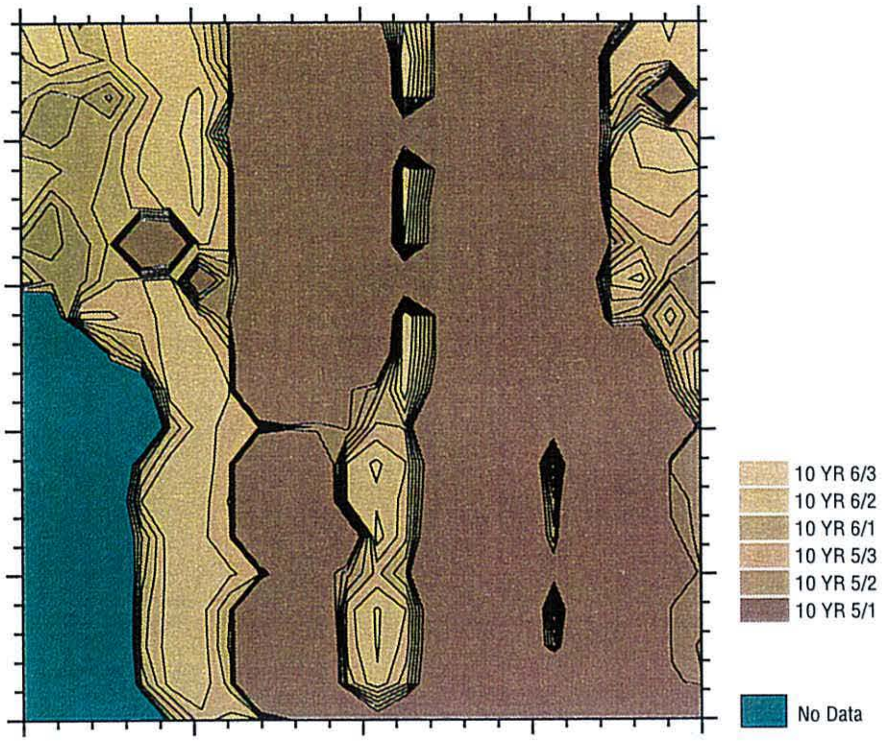


Figure 4.22 Air-dry soil colours - New Marte site

Figure 4.23 Ignited soil colours - New Marte site

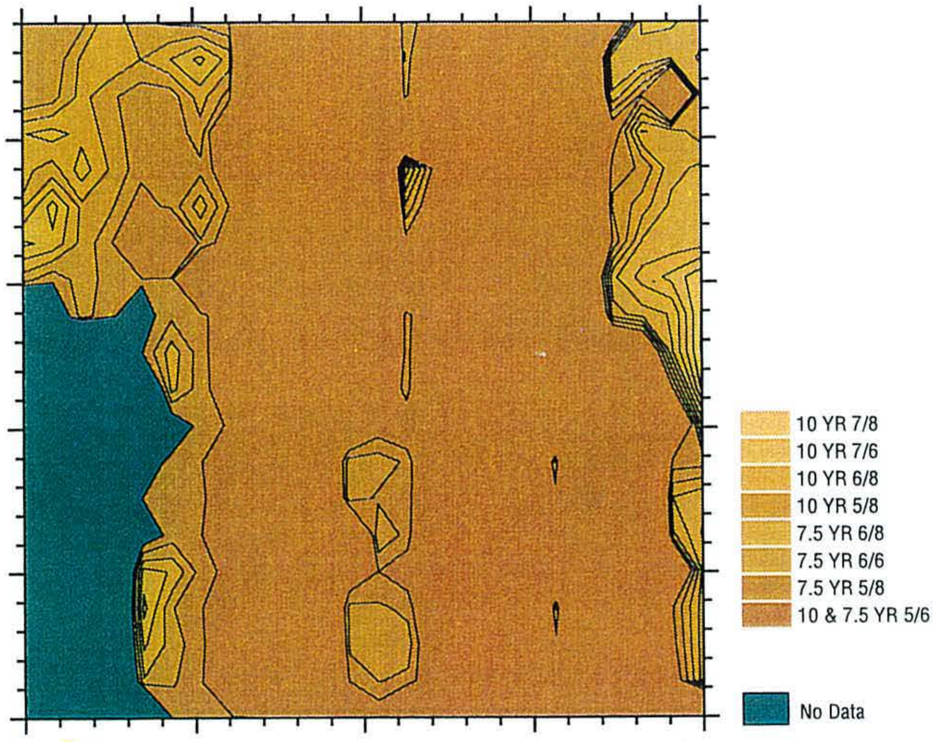


Table 4.9 - Correlation Matrix of soil colour terms and selected soil measurements

	Bulk density	Loss-on-ignition	pH water	% Sand	% Silt	% Clay	Air-dry Value	Air-dry Chroma	Ignited Hue	Ignited Value	Ignited Chroma	Air-dry CIE x	Air-dry CIE y	Air-dry CIE Y	Ignited CIE x	Ignited CIE y
Loss-on-ignition	▼															
pH water	ns	▼														
% Sand	▲	ns	▼													
% Silt	▼	ns	ns	▼▼												
% Clay	ns	ns	▲	▼▼	▲▲											
Air-dry Value	ns	ns	ns	▼	▲	ns										
Air-dry Chroma	▲	▼	ns	ns	ns	ns	ns									
Ignited Hue	ns	▲	▼	ns	ns	ns	ns	ns								
Ignited Value	ns	▼	ns	▲	▲▲	▼	ns	ns	ns							
Ignited Chroma	ns	▼	ns	ns	ns	ns	ns	ns	▲	ns						
Air-dry CIE x	▼	▼	ns	ns	ns	ns	ns	▲▲	ns	ns	ns					
Air-dry CIE y	▲	▼	ns	ns	ns	ns	ns	▲▲	ns	ns	ns	▲▲				
Air-dry CIE Y	ns	ns	ns	▼	▲	ns	▲▲	ns	ns	ns	ns	ns	ns			
Ignited CIE x	ns	ns	ns	ns	ns	ns	ns	ns	▲	▼▼	▲▲	ns	ns	ns		
Ignited CIE y	ns	ns	ns	ns	ns	ns	ns	ns	▲▲	▼	▲▲	ns	ns	ns	▼▼	
Ignited CIE Y	ns	▼	ns	▲	▼▼	▼	ns	ns	ns	▲▲	ns	ns	ns	ns	▼▼	▼

▲▲	highly correlated (+ve)	$r > 0.40$
▼▼	highly correlated (-ve)	$r < -0.40$
▲	significantly correlated (+ve)	$0.40 > r > 0.21$
▼	significantly correlated (-ve)	$-0.40 < r < -0.21$
ns	not significant $p > 0.05$, $n=90$	$-0.21 < r < 0.21$

4.7.5 Soil colour - relationship with other variables

The colour terms have been used in a correlation with several soil properties (Table 4.9) for the samples across the New Marte site. The soil properties (Bulk density, Loss-on-ignition, pH, %sand, %silt, %clay) were selected to represent physical parameters (Bulk density, texture), chemical parameters (pH) and a possible combination (Loss-on-ignition). Table 4.9 also correlates the two different soil colour definitions - Munsell and CIE 1931 (x,y,Y), thereby allowing a comparison to be made as to the more predictive system. This procedure is similar to that of Post *et al.*, (1993), who compared different methods of obtaining soil colour measurements. The correlation assumes that any relationships between the parameters will be linear. Here the CIE system may be considered more appropriate than Munsell.

4.7.6 Results

From table 4.9 it is evident that the colour terms are closely associated, both between and within the sets of Munsell and CIE 1931 terms. The lack of variation in the air-dry hue term (10YR) excludes this from the analysis. As is evident in the analysis of the soil measurements earlier (table 4.2), the soil texture parameters are interdependent and correlate with one another. All the soil texture terms, particularly silt content, correlate with the ignited soil Munsell value term and with the ignited soil CIE Y term. The Munsell value term is related to the lightness/darkness of the sample and is normally associated with the amount of organic material in the soil (*e.g.* Schulze *et al.*, 1993), but in this instance this result appears to reflect the different parent materials (and hence also texture), from a light aeolian sand to a more organic-rich and hence darker clay. The soil parameters bulk density and pH only show a small number of significant ($P<0.05$) correlations with the soil colour terms, but loss-on-ignition shows correlation with both ignited and air-dry colours. That it is correlated with both air-dry and ignited terms appears to reinforce the opinion stated earlier (section 4.6.4) that the loss-on-ignition is due to several factors, not simply organic matter content.

The differences between the two colours systems are not evident, and this may be due to the limited range of Hue terms. Overall, the soil colour measurements have shown that they are related to several of the soil parameters. However they are not sufficiently strongly correlated with any term to offer a form of prediction as to the soil field conditions, but the ignited colours may be indicative of parent materials.

4.8 Discussion of New Marte site characteristics

The results gained from these analyses of the soils across the New Marte site, at inter-plot (25 m) periodicity, have both general and specific implications. In general terms, they illustrate the inherent heterogeneity that is encountered in establishing such a large-scale experimental site; this is particularly evident in this locale where there is a mixture of lacustrine and aeolian deposits. In more specific terms, the results quantify various environmental factors and indicate others of relevance to the agroforestry experimentation for which the site was established. Whilst it may be considered desirable to have measured a larger number of variables (*e.g.* exchangeable cations), the variables selected have covered a broad range of both physical and chemical factors and have allowed a more focused approach toward soils experimentation at the plot level, which is the subject of the following chapters.

4.8.1 Characterisation of soil variability

The variability of these soils stems in part from that of their parent materials, as expressed principally in the importance of textural variations across the site. The acquired soil properties, such as pH and Total N and P, appear to vary independently. The heterogeneity of these soils offers differing conditions for the growth and establishment of the agroforestry planting, and there is also the possibility that site conditions at one position may influence those at another. For instance, areas of high surface-soil clay contents may lead to poor infiltration and increase the run-off to other areas, increasing the overall area flooded which, in turn, results in poor tree survival due to more chronic anoxic conditions.

The values obtained from the main chemical analyses (Table 4.1) are consistent with values quoted for other vertisols in world literature (West *et al.*, 1987; Probert *et al.*, 1987) and are also consistent with previous soil surveys of the region (Beavington, 1978; Carroll, 1974). This extends to include a mean C:N ratio of 12:1 in the SW block of the experiment where the clay content is higher and the vertic nature of the soils is more evident and this area can be faithfully compared with other vertisols. The C:N ratios obtained from measurements made on the sandy soils (<1:1 to 9:1) of the NE block are particularly subject to experimental and sampling error because of the very low organic matter contents (*i.e.* < 0.10 % Organic C). The inclusion of the chemical soil measurements as covariates to the analyses of the tree survival and total cross-sectional area of tree characteristics revealed no significant factor inhibiting tree performance. However the measurements of soil texture were, as expected from the mapping, found to be significant (Table 4.1). This is again re-emphasised in the domination of the first principal component by the textural parameters (Table 4.3), indicating that tree survival and soil textural parameters exhibit parallel trends. The chemical components have greater representation in the second principal component, which is orthogonal to the first.

The principal textural trend, as seen in Figures 4.2 and 4.3, shows the distinct change from sand-rich soils in the NE corner of the site (94% > 60 μm) to clay-rich soils in the SW corner (44% < 2 μm). As would be expected, the textural constituents correlate strongly with one another across the site (Table 4.2; Figure 4.18), particularly where there has been little disturbance or amendment to the parent material. The textural variations are explicable in terms of deposition at the margins of the former Lake Chad, supplemented by aeolian inputs from the Harmattan. This sandy material is seen (section 3.5) to dominate both lake sediments and the covering aeolian material. Previous work on characterising the Harmattan dust (*e.g.* McTainsh, 1984; McTainsh and Walker, 1982) has recognised its importance as a consituent part of the composition of soils from a geographic area extending across Nigeria from 10° N to 14° N (Møberg and Esu, 1991). The general picture created, corresponds with the mineralogical investigations (Chapter 3) and with the features observed in the field on the site. The seasonal ponding and vertic cracking observed in the more clay-rich soils (Section 2.4) coincides with the poorer establishment of trees in those parts.

This dominance of texture is evident in the local naming of land according to the amount of sand relative to clay within the soil (Braukämper *et al.*, 1993; Kirscht and Skorupinski, forthcoming). Parent material has thus been the major determining factor in land use. Besides the general textural trend changing from sand to clay, other soil parameters show similar parallel trends. Values of pH in the sand-rich NE corner are high and reflect the presence of calcareous material, whilst the lower pH soils in the SW appear to have no free calcareous material. This implies that the calcareous material is of aeolian origin in these surface soil samples. Where there is an influx of aeolian material, as suggested by the presence of hydrous mica in the clay fraction (section 3.3), the correlation between clay and fine clay appears weaker. As has been seen (section 3.4), the fine clay content shows an overall parallel trend with total clay content in layers other than the surface horizons, suggesting little clay size fractionation in the lacustrine deposits. The fine clay material, at whatever depth it is found, is of particular relevance to the chemical and physical behaviour of these smectite-rich soils; it will possess a relatively high cation exchange potential for its mass and will be of key importance as components in the formation of stable aggregates (Turchenek and Oades, 1978).

4.8.2 Analysis of tree measurements

The contour map of interpolated tree-survival data (figure 4.16) across the site was adjusted to remove species and year effects, with the data transformed on an angular transform scale. This allows a meaningful comparson of survival with other environmental factors of the site, rather than these two tree factors *i.e.* species and year, to be made. The mapping in figure 4.16 shows a strong North-South division between the experimental blocks 3 & 4 (north) and blocks 1 & 2 (south). The greater tree survival in the northern blocks was the major criterion in selecting these two experimental blocks for use in the detailed site experimentation (see section 1.8). This indicates that either the tree species selected, or the establishment techniques used could be improved for the southern blocks (1 & 2) where tree establishment was poorest.

The influence of the soil on the agroforestry experimentation is reflected in the survival rate of trees from the initial phases of planting and it has been shown (Table 4.2) that the tree survival has strong correlations with the inherited soil properties, particularly with % sand ($P<0.05$, $r=+0.60$). The variograms for the sand and clay show readily discernible trends of increasing semi-variance with distance. However, the tree survival variogram does not, showing similar semi-variance with distance: this is a result of greater variability at short spatial distances of survival (Figure 4.16) compared with the textural properties (Figures 4.1 and 4.2).

4.8.3 Implications for land-use

The physical impact of soil texture on tree establishment and growth will be two-fold. First, there is the difference in the growth and extension of rooting systems which are most likely to prosper in the friable sandy areas relative to the clay soil areas. This is despite the lower water holding capacity of the sand and the surface crust that occurs in parts of this sandy area which, coupled with the topography, induces run-off toward the area of clays, thereby reducing the amount of residual moisture available for the subsequent growth of plants in the sandy areas. Second, root damage may result from the shrinkage within the soils with the higher clay contents during the dry season. This last factor may been seen in the tree species adaptation to soil conditions at sites elsewhere. In the Sudan with vertisolic soils similar to those at New Marte, Adams (1967) reported clearly distinct differences in the morphology and biomass of the root system, particularly lateral root development, between mature examples of *Acacia seyal* and *Balanites aegyptiaca.* Latterly Fagg (1991 - reported in Giller and Wilson, 1991) has examined tap roots on *Acacia* species extending to very great depths in the southern Sahara. In agroforestry systems in semi-arid conditions, such differences below-ground, arising from the spatial distribution, biomass production and turnover of tree roots, are considered to influence soil conditions and competition with any intercrop more than above-ground growth (Ong *et al.*, 1991). Whilst this implies that the soil is affected by the trees and cropping, the interaction is undoubtedly two-way; it has been demonstrated that when the same tree species is grown on two different soil types the spatial distribution of the roots, particularly surface roots, can be very different (Giller and Wilson, 1991).

The data for tree survival therefore suggest that management practices, such as agroforestry and intercropping which affect soil structure and infiltration rates, may ameliorate the effects of soil texture through their modification of the water regimes, and so increase the primary productivity of the land in use. Studies of such modifications are, of course, the primary aim of the more detailed experimentation at New Marte (see section 1.8).

The growth of crops of pearl millet (*Pennisetum glaucum*) has been found to vary at spatial scales relevant to the farmer (1-200 m) on other soil types (Psammentic Ustalfs) in the Sahel region (West *et al.*, 1987; Scott-Wendt *et al.*, 1988; Manu *et al.*, 1990, 1991; Brouwer *et al.*, 1992; Geiger and Manu, 1993). Also, variations in tree growth in the Sahel have been linked to soil changes induced by meso-faunal (termite) activity (Miedema, 1994; Brouwer *et al.*, 1993). Lamers *et al.* (1995) have recorded how local farmers exploit this microvariability in soil properties within their agricultural practices, matching plant requirements to site variations, including both those which are inherent and those caused by the presence of woody vegetation.

At this inter-plot (25 m) level, the soil analyses carried out over the experimental site at New Marte have illustrated the heterogeneity that can exist within such areas. Moorman and Kang (1978) recorded that such heterogeneity exists at still smaller-scale levels (<25 m) in other West African soils and these authors were among the first to publish their thoughts on the implications for land-use. This survey has identified a number of inherited factors that will influence plant growth on the site. To be able to take these factors into account for crop experimentation a special purpose survey identifying relevant properties, such as that reported at smaller-scales in the following chapters, is required to achieve sufficient predictive accuracy (Dent and Young, 1981).

5 PLOT-LEVEL EXAMINATION OF NEW MARTE SOILS

The variability of the soil at an inter-plot level (>25 m) across the New Marte site was the subject of the previous chapter, with the regional, more general, soil characteristics presented in chapters 2 & 3. In this chapter, the spatial variation of surface properties at a smaller scale within plots (an intra-plot level), over distances of 1-25 m, are investigated and their implications discussed. General soil characteristics at this plot level of experimentation are also discussed in this chapter. Chapters 6, 7 and 8 which follow this are all focussed at this same plot level of experimentation; they respectively cover soil structure, infiltration and soil nutrient inputs.

5.1 INTRODUCTION

To follow the site-wide inter-plot examination of the characteristics of the soils at New Marte, a more detailed set of measurements have been made at an intra-plot level. These have included measurements relating to presence or absence of trees and are examined with regard to three stated aims which form distinct aspects of the hypothesis (see section 1.3.2) of the experimentation across the whole experimental site. These aims are:

a) detailed characterisation of the soils, thereby allowing the comparison of soil factors with themselves.

b) comparison of basic tree measurement with soil parameters, with the objective of identifying any influence that the trees may have had on the soil.

c) characterising nutrient inputs to the soil (to be discussed in chapter 8)

The first two of these aims have both been addressed in two ways: a series of direct field measurements and examination of samples in the laboratory. The procedures used and results obtained are detailed first (sections 5.2 - 5.4), with the results posted alongside the description of each method. These sections are followed by a statistical summary (section 5.5) and discussion and conclusions (section 5.6) drawn from the results.

5.1.1 Spatial level

At the inter-plot (>25 m) spatial level the initial survival of the trees was found to be related to the inherited soil characteristics rather than soil properties acquired through pedogenesis. The variability of the soils was shown to derive, in large part, from that of their parent materials, as expressed principally in the importance of textural variations across the site, although some of the acquired soil properties, such as pH and EC, would appear to vary independently. Since the experimental design at the lowest experimental (*i.e.* plot) level has double replication (see figures 1.18 and 1.19), this allows comparative experiments and trials to be performed on a single tree species with trees of the same age. This allows the spatial variation of soil surface properties at an intra-plot level (1-25 m) to be described and relationships between both the physical (penetration resistance, depth of sand layer, bulk-density) and chemical (Total N, Total P, % Organic matter, pH, loss-on-ignition) parameters discussed. Similarly, the relationship between the planted spaced trees and the soil properties can be examined.

5.1.2 Previous work

World-wide, small-scale variability of soils has traditionally been seen as a problem both for taxonomic classification and for the interpretations made of agricultural experiments (Nielsen and Bouma, 1985). It has been appreciated only relatively recently that quite small-scale variations in soil and site conditions can be major a factor in subsistence farming (Mormann and Kang, 1978). Presently, there is growing evidence of the importance of small-scale (<50 m) variability within the management of the resources available to farmers in semi-arid areas, particularly the Sahel (Lamers, *et al.*, 1995).

In the Sahelian climatic region variability in the agronomic performance of staple crops (millet, sorghum) has been recorded at distances from 1 to 200 m. A large amount of work in this region has originated from the ICRISAT Sahelian centre at Niamey (13°20' N 2°0' E) which has a similar, if drier climate to that of New Marte (FAO, 1984). Various possible explanations have been offered for these small-scale variations in crop performance. These range from farming practices (*e.g.* timing of crop planting and weeding) (Brouwer, *et al.*, 1993) to the relative proximity of trees where there has been much discussion of the potentially beneficial effects to millet and sorghum growth of the tree species *Acacia (Faidherbia) albida* in agroforestry systems (Vandenbeldt, 1992). These trees typically occur infrequently (1-10 ha^{-1}), often remaining as relicts from past vegetation (cf. Foster, 1914), and they help form cultivated parkland which is a typical farming system of the Sahel.

Other explanations for small-scale variability include termite activity (Brouwer *et al.*, 1992; see section 3.4) and inherited soil characteristics. This would indicate that agronomically unproductive soils accentuate their condition, thus increasingly marginalizing productive soil resources, whilst the remaining uncultivated and unplanted land is left to be further denuded by the agents of erosion. Research on other soils, albeit in more temperate locations, has suggested that small changes in topography, sometimes called a "random roughness" factor (Allmaras *et al.*, 1991), are particularly important in minimising soil erosion through water movement. This is particularly relevant to the formation and development of soil crusts and it has been found that one of the major factors in crust formation in the Sahelian region is through water movement over the soil surface (Valentin, 1992).

5.1.3 Selection of plots for detailed study

In order to undertake detailed field measurements, a small number of plots were selected from the 30 ha field site. The criteria for selecting a subset of the plots were:

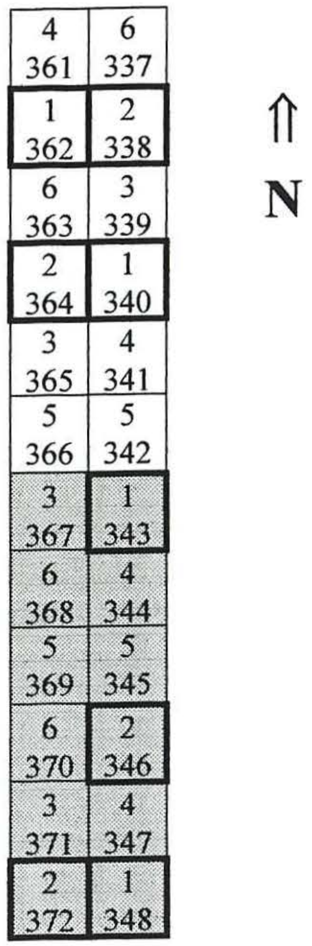
a) a potentially useful tree species (judged from tree growth, usefulness of the tree products and tree survival from planting)
b) one planting year (*cf.* section 1.8)
c) one block of the experimental design

The two most successful tree species in the initial phase of experimentation on the site (1987-1991) were *Acacia nilotica* together with the naturalised species *Prosopis juliflora.* In this initial growth period there was little difference in the performance of these two species. *Acacia nilotica* was selected for further study since it was considered to have a better canopy shape for intercropping, and it is an indigenous species.

The selection of one planting year and one experimental block was made from the results of the initial tree survival (section 4.3). These results revealed that the 1988 planting year and blocks 3 & 4 (the northern blocks of the experimental site) were the most complete plots (in terms of tree material) with which to undertake detailed experiments. On this basis, a total of eight *A. nilotica* and control plots first planted in 1988 (Figure 5.1) from block 4 of the field site were used for the measurements and analyses described in the following sections. Half of the tree plots and half of the control (no tree) plots were intercropped with a local landrace of *Sorghum bicolor*. Until 1993 the planting of sorghum took place at a density of 10,000 plants ha^{-1} (1 m spacing); in 1994 this was reduced to 6,400 plants ha^{-1} (1.25 m spacing). Therefore, within this set of plots, the treatment structure is:

2 tree treatments (control *vs. Acacia nilotica*)
2 cropping treatments (control *vs.* sorghum)
2 replications (Figure 5.1).

Figure 5.1 Plots at New Marte Experimental site: Block 4, 1988 planting



Key

Plots intercropped with sorghum

Plots used in the experimentation described in this chapter

1	Tree species
379	Plot number

Key to Tree Species

1 Control - no trees
2 *Acacia nilotica*
3 *Acacia seyal*
4 *Acacia senegal*
5 *Balanites aegyptiaca*
6 *Prosopis juliflora*

5.2 SAMPLING METHODS

5.2.1 Soil Measurements

Field measurements and sampling were undertaken during the 1993/4 field season. With the exception of the measurement of the plot topography, which was recorded over all of the plot area, measurements and sampling have been made within the central 15 m x 15 m area of each plot. Since the trees are planted on a regular 5 m x 5 m grid, for the four plots planted with *Acacia nilotica*, this area contains the central nine trees.

For each plot, 20 randomly selected positions on the nodes of a 1 m grid were located within the 225 m^2 central area. These positions were subject to both the field measurement of soil parameters and sampling for laboratory analysis. The randomisation of the sampling positions was different for each plot, figures 5.2-5.9 show these positions. In June 1993, at each sampling position, two replicate samples for bulk density and gravimetric moisture measurements were taken in 50 mm diameter steel "*p*F" rings. Additionally, soil cores (0-50 cm) were obtained for the chemical studies. These cores were then sub-divided into 0-10 cm and 10-50 cm depth sections, and the former used for the subsequent analyses.

5.2.2 Other measurements

In addition to the soil sampling and field measurement of soil properties, other sampling positions were located within the central 15 m by 15 m area. These included exclusion boxes for biomass decay measurements ("biomass boxes"), litter-fall and throughfall collectors for nutrient input measurements (see sections 8.1 - 8.3 later). The positions of these sampling devices are also shown in figures 5.2 - 5.9.

Figures 5.2 - 5.9: Mapping of the locations of sampling points in the plots used at New Marte for detailed experimentation.

A map of each of the 8 plots used from the Block 4, 1988 year of planting (see figures 5.1, 1.18 and 1.19.). Each map represents the central 15 m by 15 m portion of each plot.

Figure 5.2 Map of sampling positions in Plot 362

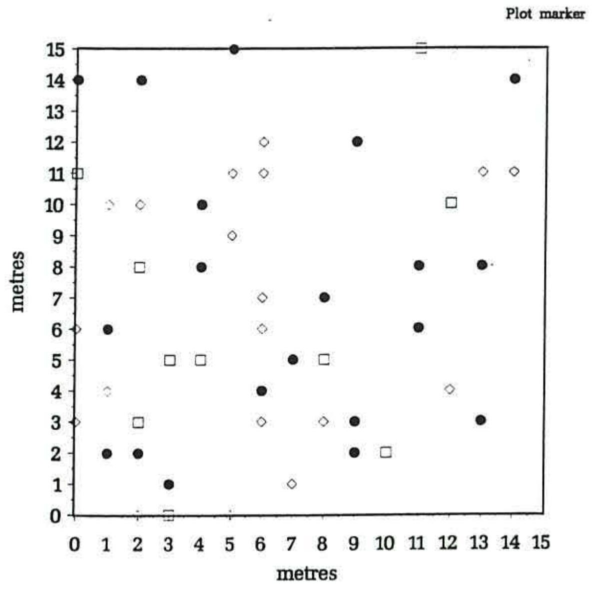


Figure 5.3 Map of sampling positions in Plot 338

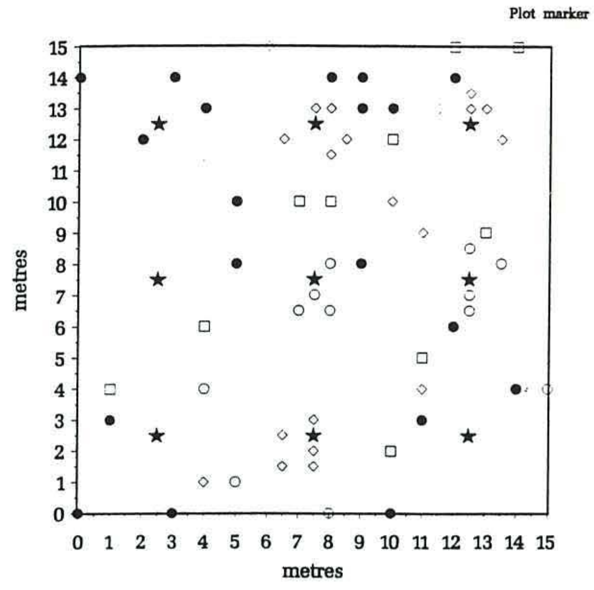


Figure 5.4 Map of sampling positions in Plot 364

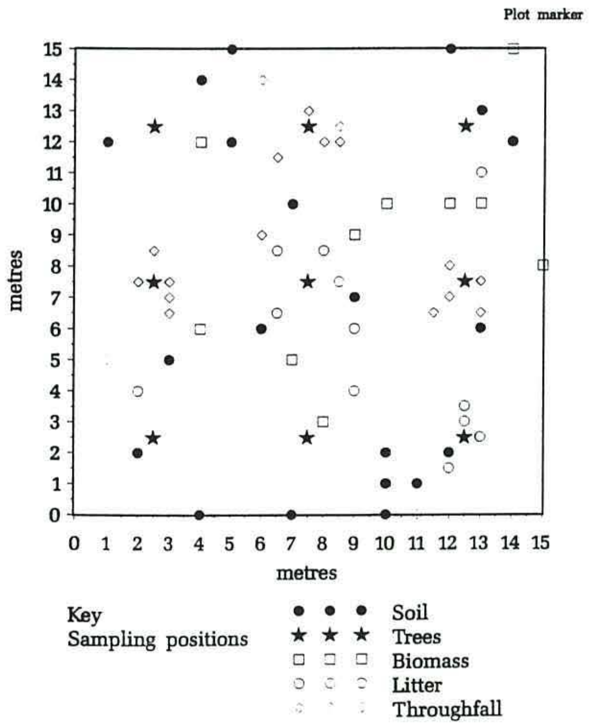


Figure 5.5 Map of sampling positions in Plot 340

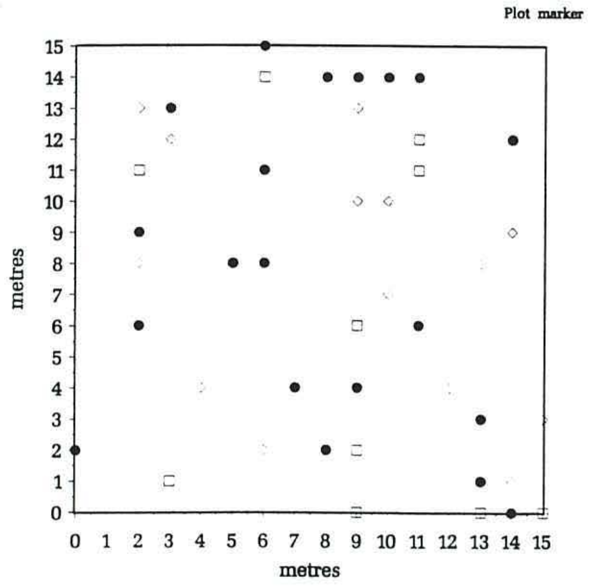


Figure 5.6 Map of sampling positions in Plot 343

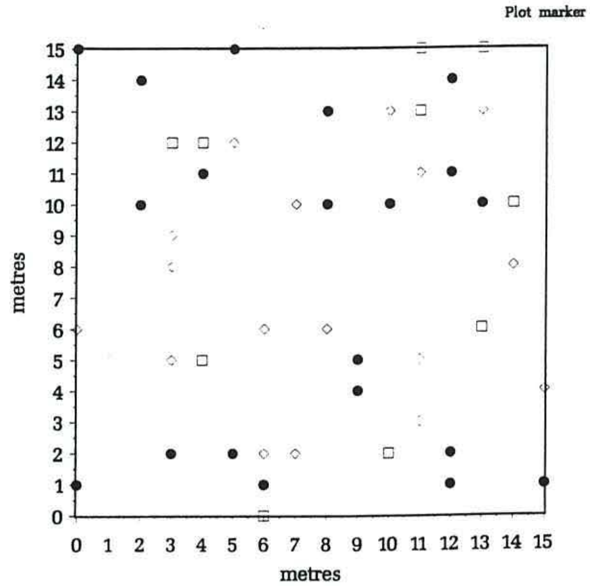


Figure 5.7 Map of sampling positions in Plot 346

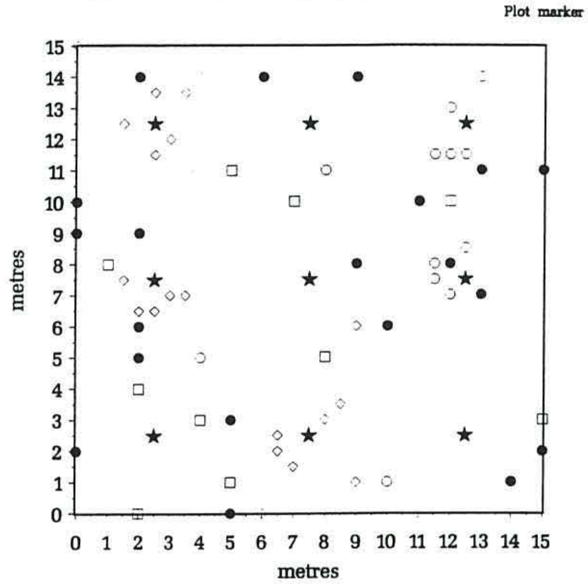


Figure 5.8 Map of sampling positions in Plot 372

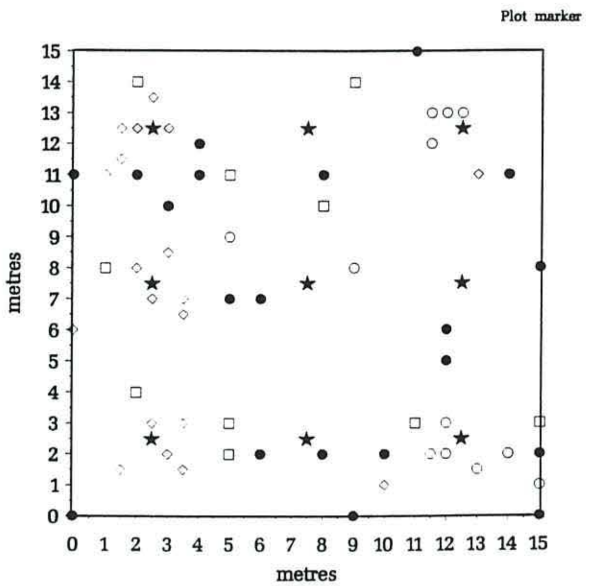
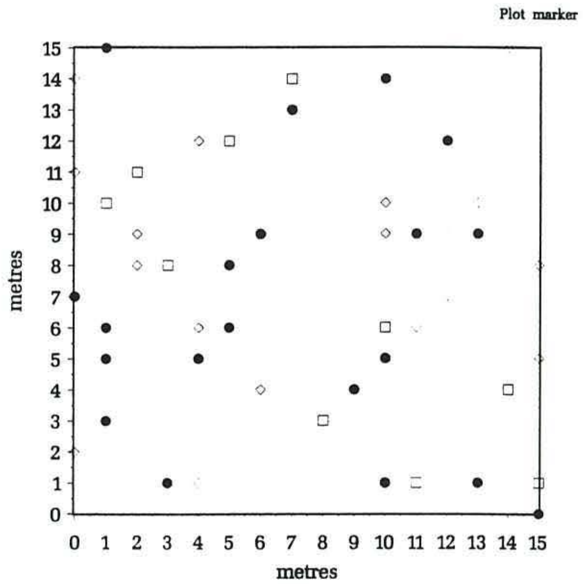


Figure 5.9 Map of sampling positions in Plot 348



Key
Sampling positions
● ● ● Soil
★ ★ ★ Trees
□ □ □ Biomass
○ ○ ○ Litter
◇ ◇ ◇ Throughfall

5.3 FIELD MEASUREMENTS - METHODS AND RESULTS

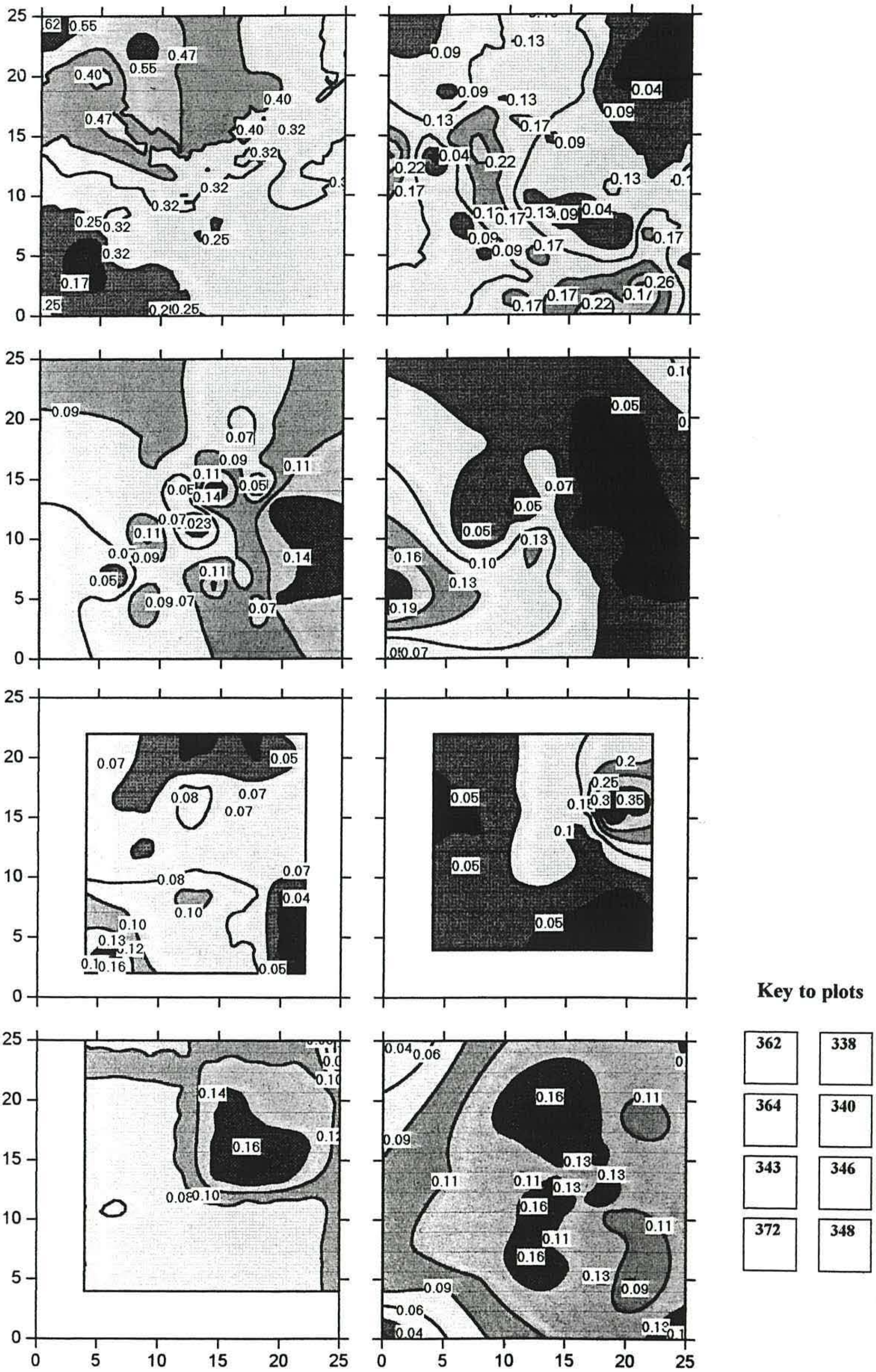
5.3.1 Levelling

The microtopography of the plots was assessed by levelling using an Eijkelkamp levelling apparatus (Model 09.01), ranging rods and conventional tape measures. Electronic distance measuring (EDM) levelling apparatus was not available for use, therefore the measurements made are subject to greater errors in the horizontal plane (± 3 %) than is now considered normal with EDM results whereas errors in vertical measurement are ± 1 cm (± 1 %). The levelling results have been mapped in two ways. Firstly, on a plot by plot basis (Figure 5.10) where the raw levelling data has been interpolated onto 0.5m grid nodes across the complete plot area (25 m x 25 m), with each plot having its own vertical scale. Secondly, with data interpolated onto 5.0 m grid nodes, as a map (Figure 5.11) across the whole area (50 m x 275 m) covering the eight site plots (*cf.* Figure 5.1).

5.3.2 Depth of sand layer

The depth of sand layer was measured at the sampling positions within the plots. By use of a 2 cm diameter screw auger, the depth of sand was discriminated as the depth at which a distinctly sandy texture could no longer be felt by hand (± *ca.* 3 cm). The results for each plot have been mapped using Unimap software (UNIRAS, 1990), with the results interpolated between the sampling points (see figure 5.2-5.9) onto a 40 by 40 node grid. The scale for each plot map encompasses the range of the measured quantity across all eight plots. This same procedure has been undertaken for all of the soil physical and chemical measurements and the resulting maps are shown along with the description of the measurement in the following sections. The depth of sand layer across the site plots is shown in the plot maps of figure 5.12.

Figure 5.10 Microtopography of site plots
Distances in metres. Elevations (m) above lowest point in each plot
Contour interpolation not performed where < 2 data per square metre



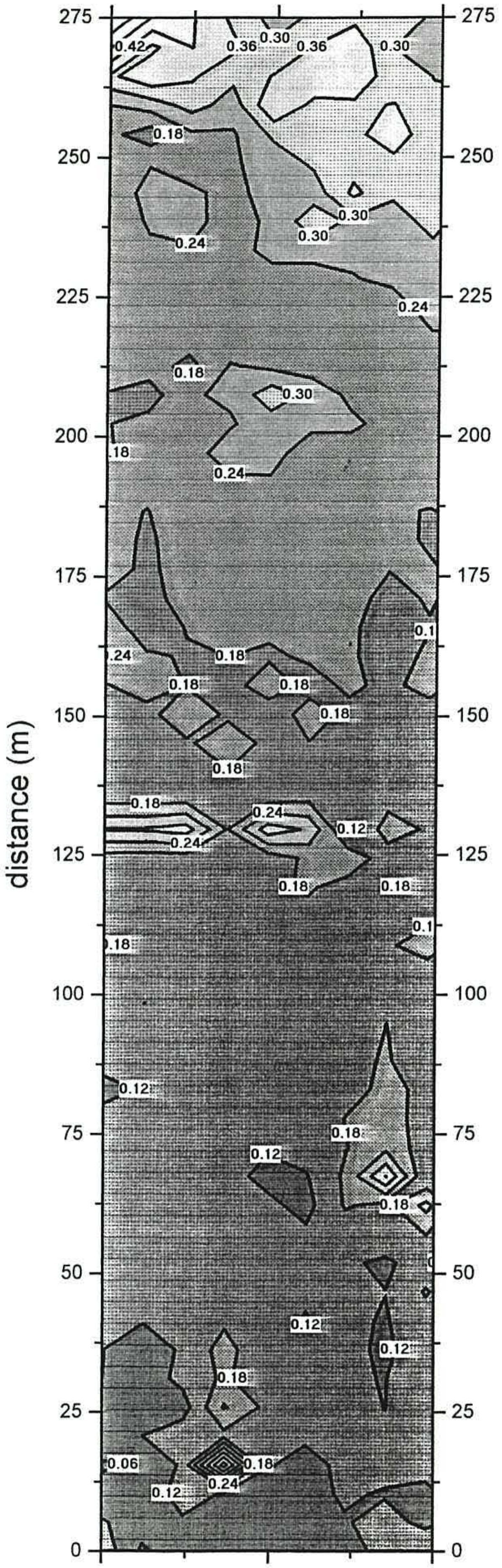


Figure 5.11

Microtopography of area containing plots 362/338 to 372/348 (*c.f.* Figure 5.1)

Height (m) above lowest point

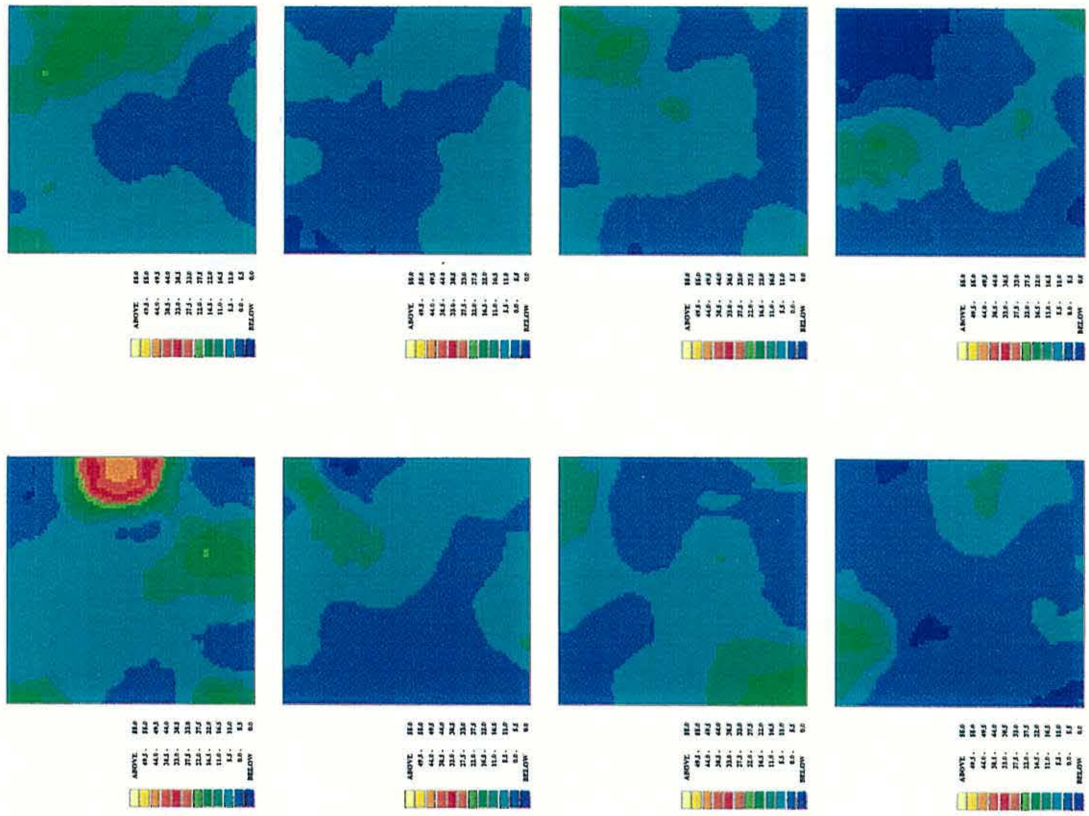


Figure 5.13 Depth of penetration resistance at 100 N/cm

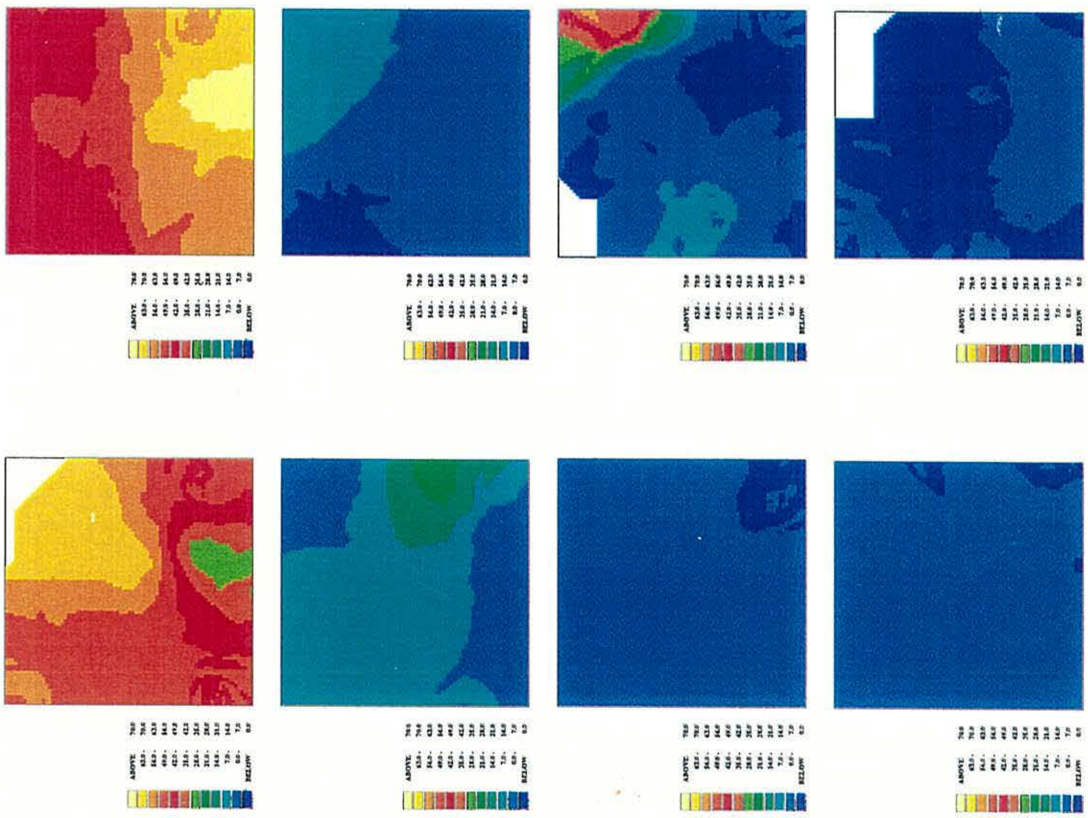
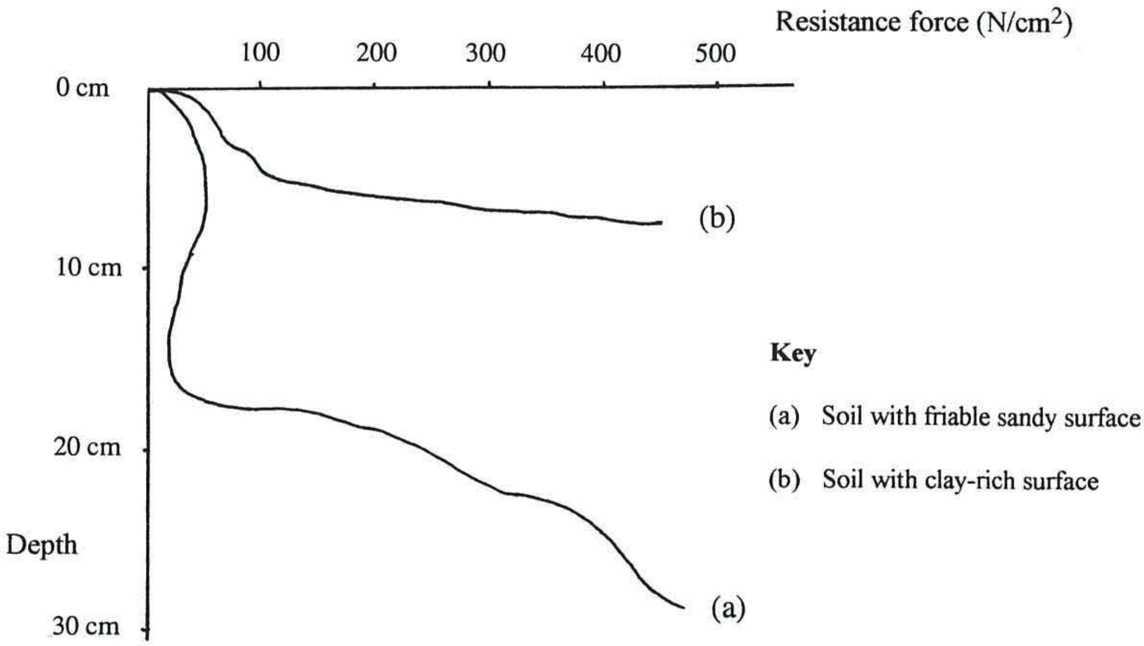


Figure 5.12 Depth of Sand layer

5.3.3 Penetration resistance

Vertical penetration resistance of the soil was directly measured using portable equipment. Penetrometer measurements were made using a self-registering Eijkelkamp penetrometer (model 06.02 Stiboka penetrograph). The penetrometer measurements were made in a 48 hour period in September 1993, after the end of the major rainfall events for the year's rainy season. The device measures the penetration resistance of soils up to a maximum depth of 80 cm. For each measurement a paper trace is produced, recording the continuous measurement of penetration resistance *versus* depth. Example traces are shown in Figure 5.14. These show the results from two very different locations within the plots, one clay-rich, one sandy.

Figure 5.14 Penetration resistance - example traces



These raw continuous data generated by the penetrometer, have been resolved to three arbitrary measurements: the depths at which nominal penetration resistances (100 N cm^{-2}, 200 N cm^{-2}, 300 N cm^{-2}) are found in the soil profile. If the penetration resistance dropped at any point in the profile (see figure 5.14), for instance if a large void was penetrated, then the depth at which the resistance force was first experienced is recorded. These quantified penetrometer readings taken from the three threshold forces of 100 N/cm^2, 200 N/cm^2 and 300 N/cm^2 have been plotted as a series of interpolated maps of the central 15 m x 15 m sections of each plot (Figs 5.13, 5.15, 5.16).

Figure 5.15 Depth of penetration resistance at 200 N/cm

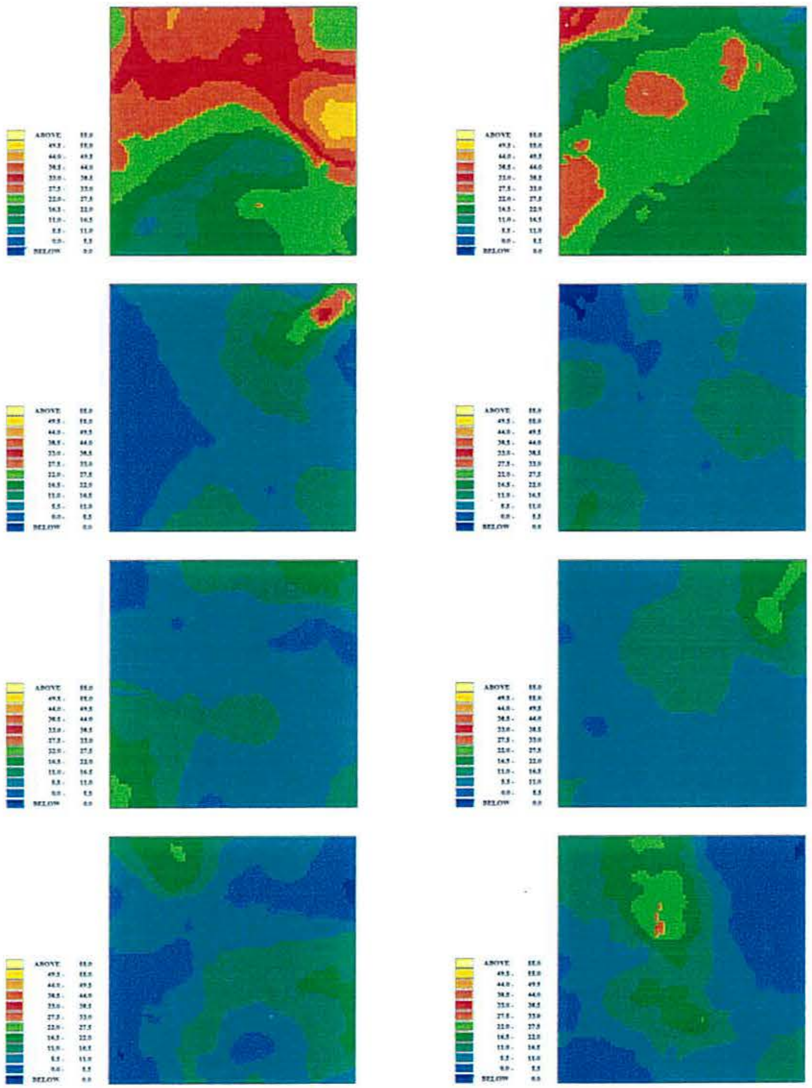
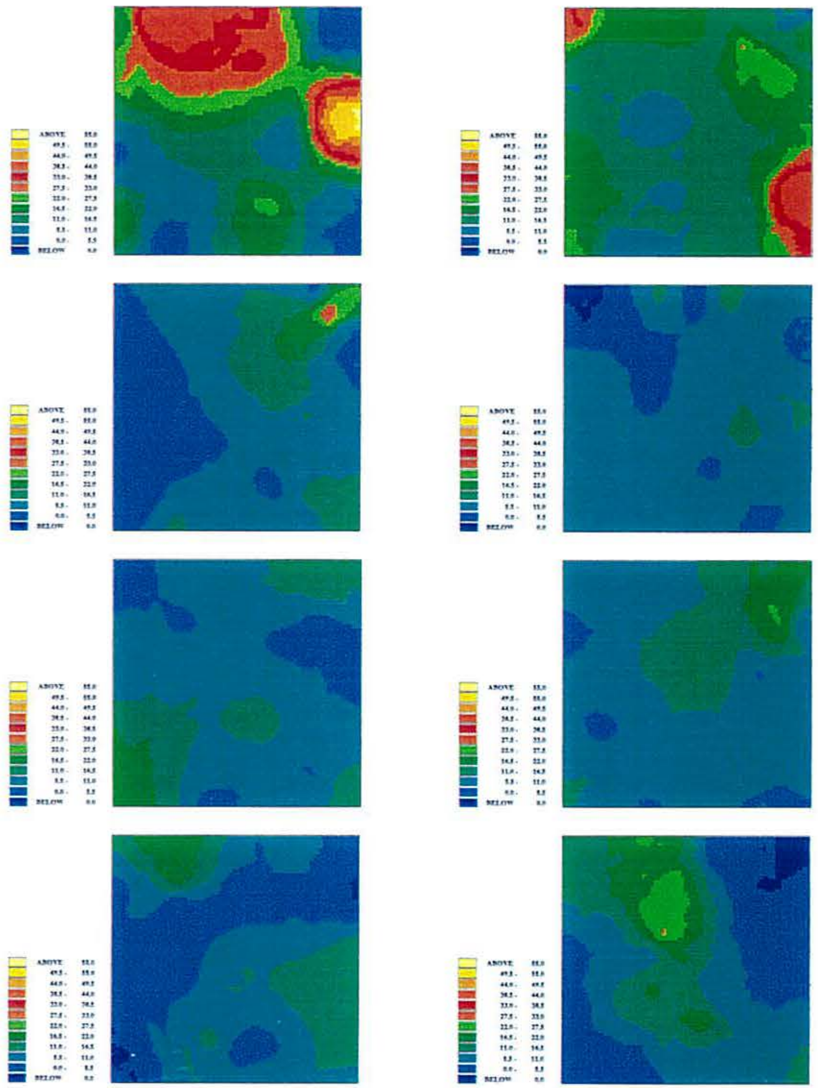


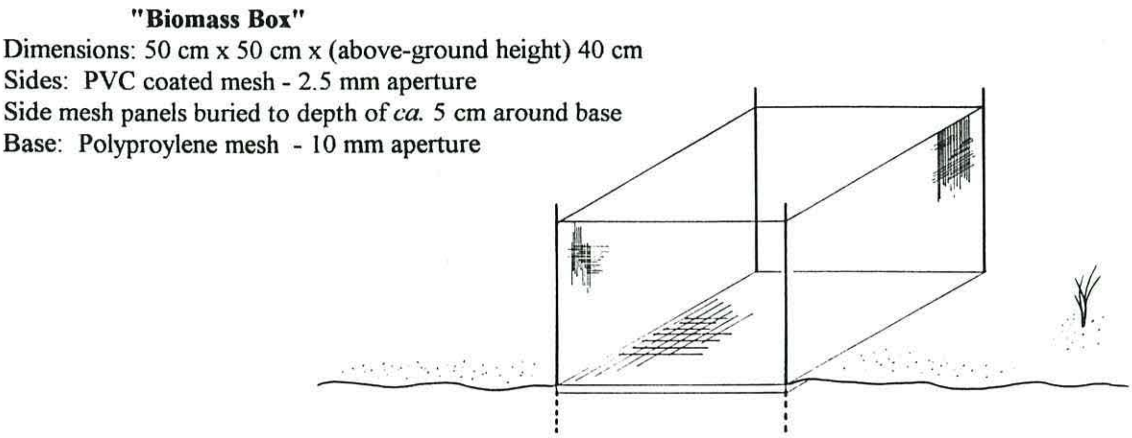
Figure 5.16 Depth of penetration resistance at 300 N/cm



5.3.4 Plants identification

The distribution of the plant species was assessed across the eight plots intensively investigated. To obtain the plant material for identification, all of the above-ground material in two 50 cm x 50 cm quadrats was harvested from each site plot. These quadrats were marked in September 1993 and were protected from the effects of the agroforestry experimentation, such as weeding and planting of sorghum, by the mesh "biomass box" constructed around them (see figure 5.17). The harvesting was undertaken in January 1995 at the end of the growing season thereby representing the plants growing on the residual moisture, rather than the hydrophytic plant community that flourishes immediately after the onset of the rainy season (June/July). Intuitively, it is the plants growing on the residual moisture which develop the larger root systems as they follow the drying front down the soil profile, and are therefore the most important in terms of soil processes, in particular soil stabilisation. As previously described, there are distinct soil trends across these eight plots, therefore the distribution of plant species could be indicative of the range of soils encountered over a wider geographic region. The plants were identified (Table 5.1) using the general flora produced by Hutchinson and Dalziel (1954) and the woody plant guide of von Maydell (1990). Further taxonomic information on species and family classification was obtained from the standard text of Willis (1951). Plates showing plant species characteristic of different conditions on the site are reproduced in appendix 4.

Figure 5.17 Design of biomass boxes



5.3.5 Tree measurements

For all (25) trees in each plot, measurements of the main tree stem(s) at 10 cm above ground were made using callipers and tapes, whilst the crown radius at eight different radii (N, NE, E, SE, S, SW, W, NW) and the height were measured using tapes and extending ranging poles. The multi-stemmed form of *A. nilotica* makes stem measurements at positions higher than 10 cm less representative of the tree. From these measurements the stem circumference and the mean canopy radius were calculated.

5.4 LABORATORY PROCEDURES - METHODS

In order to complement the direct field measurements of soil properties, a variety of chemical and physical measurements have been made on the samples taken at the positions indicated in figures 5.2-5.9. The selection of the variables measured and the methodology was made in order to complement the preceding site-level measurements within reasoned budgetary and logistical practicalities. Therefore potentially limiting factors such as micronutrient availability were not considered here but instead analyses were focused upon the major characterising soil factors, particularly those indicative of soil changes due to the agroforestry tree planting.

5.4.1 Chemical

After the availability of water the most likely limiting factors for plant growth at New Marte are the availability of N and P. In many semi-arid environments, P has long been considered the most limiting nutrient factor (Russell, 1973). Total N has been measured using an Kjel Foss N analyser (Foss Electric Ltd.), total P by nitric acid digestion with inductively-coupled-plasma emission spectroscopy (NRM Jealott's Hill Laboratories, standard procedures). Extractable (Olsen) P was also measured using the bicarbonate extraction method standardised by Jackson (1958) and adopted by the USDA (Black, 1965 with revisions by Page *et al.*, 1982). Whilst there are many methods of extraction and analysis, the Olsen method is considered (Landon, 1991) best suited to soils where their pH is greater than 6.5, and was therefore the method of choice for these New Marte soils.

Organic matter was measured by the Walkley-Black wet oxidation method (Hesse, 1971; Page *et al.*, 1982). The Van Bremmelen factor applied to convert from % organic C to % organic matter was 1.742 (Jackson, 1958). Loss-on-ignition (450 °C) and gravimetric soil moisture content were measured using standard methods (Klute, 1986; Landon, 1991). Values for pH were measured with soil:water and soil:1M $CaCl_2$ mixtures 1:2.5 specified by Page *et al.*, (1982). The electrical conductivity was measured using a 1:5 soil:water mixture. This ratio is recommended by Landon (1991) for conductivity measurements with soils where saturation extracts are impractical to obtain.

These measurements were made on all of the surface (0-10 cm) soils. A small number of variables (pH, LOI, colour) were also made on the lower (10-50 cm) sections of the soil cores taken. Additionally, for two selected sets of twenty soil samples from both the surface (0-10 cm) and lower (10-50 cm) where the pH > 6.5, the carbonate (presumed $CaCO_3$) content was estimated using a calcimeter (see section 3.3).

5.4.2 Soil Colour

For both the surface (0-10 cm) and lower (10-50 cm) soils, colour has been assessed and analysed using the same procedure as outlined in section 4.7. The colours of these samples at all sampling locations are used in the statistical analysis of results (see section 5.6).

5.4.3 Physical

In addition to the depth of sand layer measurements the bulk density of two replicate samples from each position (see figures 5.2 - 5.9) was measured using the standard proceedure outlined in Landon (1991).

5.5 RESULTS

The results examined in this section fall into two categories. First are the identification and semi-quantitative counting of the abundance of natural plant material harvested from the plots. Secondly there are the chemical and physical measurements of the soils both from field observations and laboratory analysis. Additionally, these soils results are examined in the context of the tree growth parameters.

The results of the field and laboratory analyses have been presented in several different formats. First, graphical mapping of the plot results as a series of interpolated images. Second, direct comparison of the values obtained between a) plots where trees have been planted and b) plots without trees. Thirdly and finally, these results have been examined in relation to their spatial component to show linear and other trends evident in the measurements across the plots. Appendix V contains a series of data sets, the files containing the raw data used for both the mapping and statistical analyses presented.

5.5.1 Plant identification

The results of the plant identification are shown in Table 5.1 where the relative abundances are shown along with species and family names of the plants. There are only five families represented and of these the Graminacae are dominant with smaller numbers of leguminosae and compositae. Single specimens of species from the malvaceae and caryophylaceae families were also found. Across all the plots there was above-ground evidence of the trees which had previously occupied the field site. No attempt was made to quantify the distribution of soil faunal populations which may be related to plant distribution. The termites seen in greatest abundance (*Macrotermes sp.*) did not produce many distinctive above ground features which could have been readily mapped. The effect of the termites, ants and other soil fauna will be considerable, particularly with regard to organic material redistribution.

Table 5.1 Matrix of plant identification results

Sampling date: 25.1.95
Abundance (visually estimated) indicated from ◆ (minimum) to ◆◆◆◆◆ (maximum) as a proportion of each sample

Plot number		362	338	364	340	343	346	372	348
Biomass box number		5	15	25	35	45	55	65	75
Plant species	Family								
Cenchrus biflorus	Gramineae	◆◆◆◆◆	◆◆◆◆◆						
Zornia glochidiata	Leguminosae	◆							
Sphaeranthus senegelensis	Compositae	◆	◆	◆		◆◆◆	◆◆	◆◆◆◆	◆
Aristida adscensionis	Gramineae		◆◆			◆			
Schoenefelidia gracilis	Gramineae			◆◆◆◆	◆◆◆◆				
Cassia sp. (including *C. Tora*)	Leguminosae			◆					◆◆
Chloris sp. cf. *gayana*	Gramineae			◆		◆	◆◆		
Wild Millet, *Pennisetum* sp.	Gramineae		◆		◆	◆			
Chloris prieurii	Gramineae				◆				
cf. *Brachiaria*	Gramineae				◆		◆	◆◆	◆◆
cf. *Gnaphalium*	Compositae					◆◆			
Sida sp.	Malvacae								◆
Caryophylaceae (?)	Caryophylaceae		◆						

5.5.2 Interpolated mapping of plot measurements

As for the direct physical field measurements (section 5.3.2 - 5.3.3), the variations across the central 15 m x 15 m sections of the plots have been individually mapped using the same interpolation method and the same presentation software. The scale of measurement covers the range over all plots. The results of a selected set of measurements on the surface (0-10 cm) soil samples are presented in figures 5.18 - 5.23. These were chosen since they allow a visual comparison with the mapping of several variables across the whole site (figures 4.2 - 4.11). Figure 5.24 is an overlay to the preceding six figures and shows the canopy sizes of the trees on the appropriate plots.

Key to layout of plots in figures 5.18 - 5.24
(*cf.* Figure 5.1)

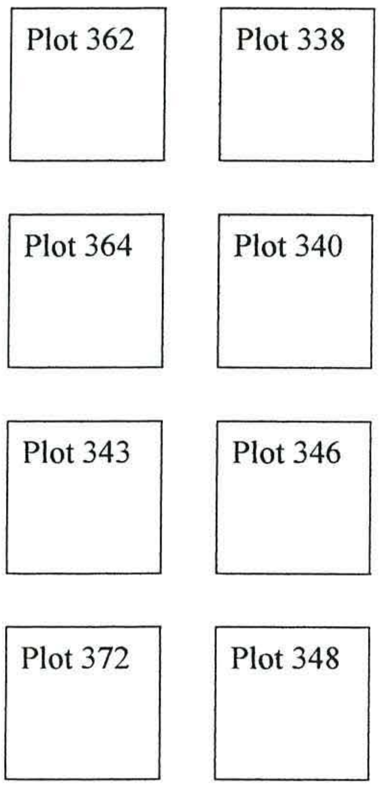


Figure 5.18 pH (H_2O) of surface (0-10 cm) soil samples

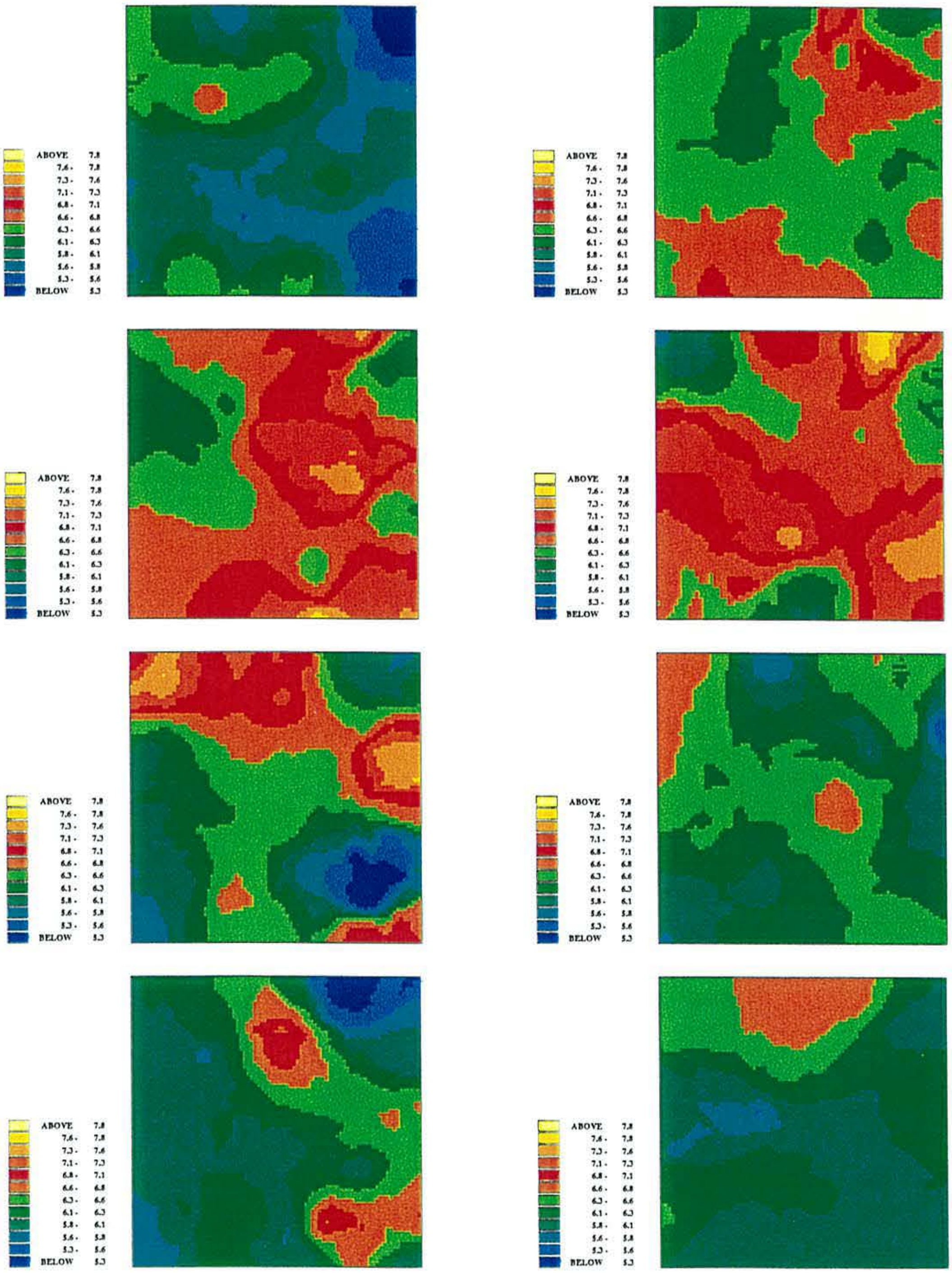


Figure 5.19 Loss-on-ignition of surface (0-10 cm) soil samples

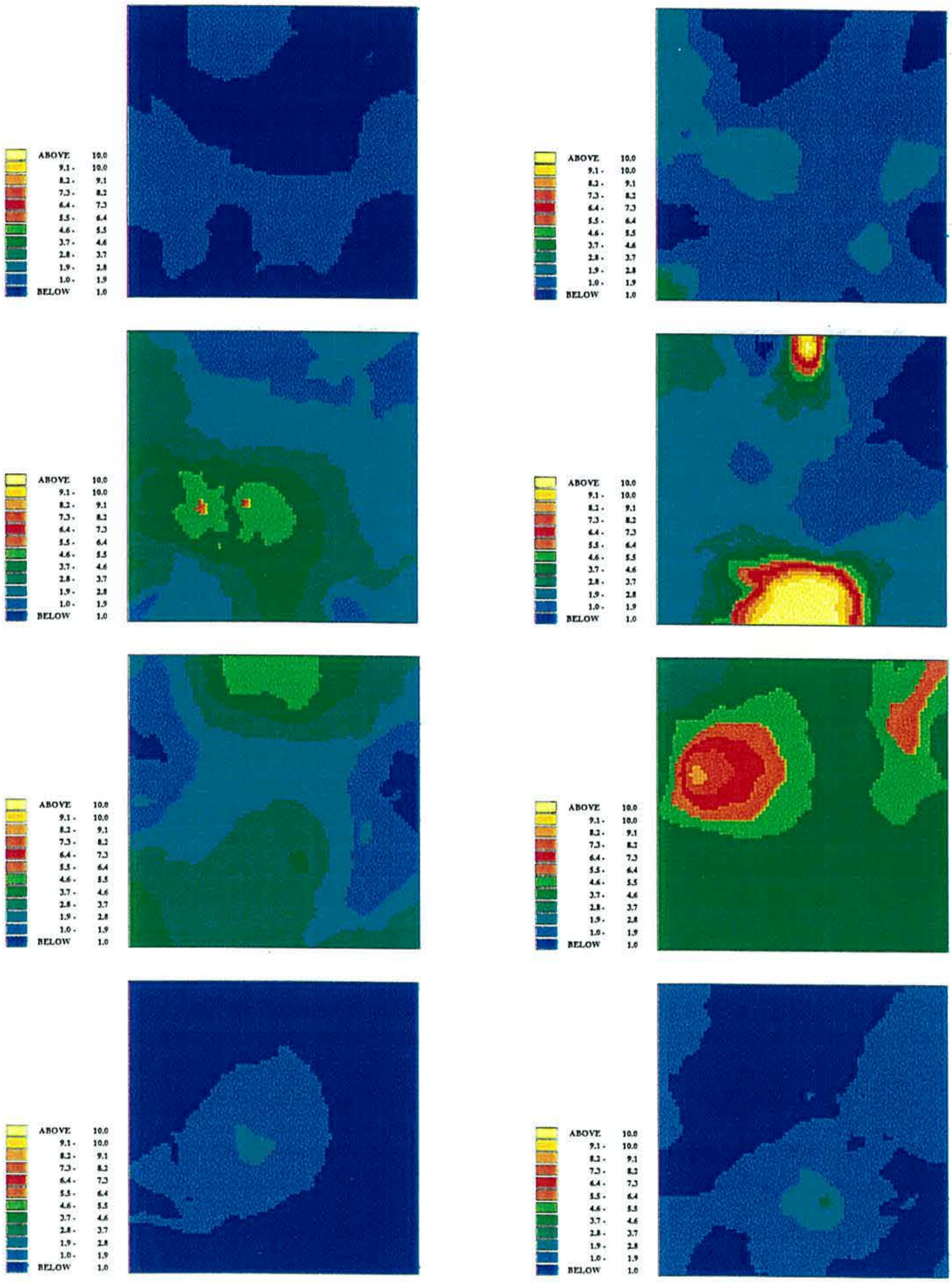


Figure 5.20 Bulk density of surface (0-10 cm) soil samples

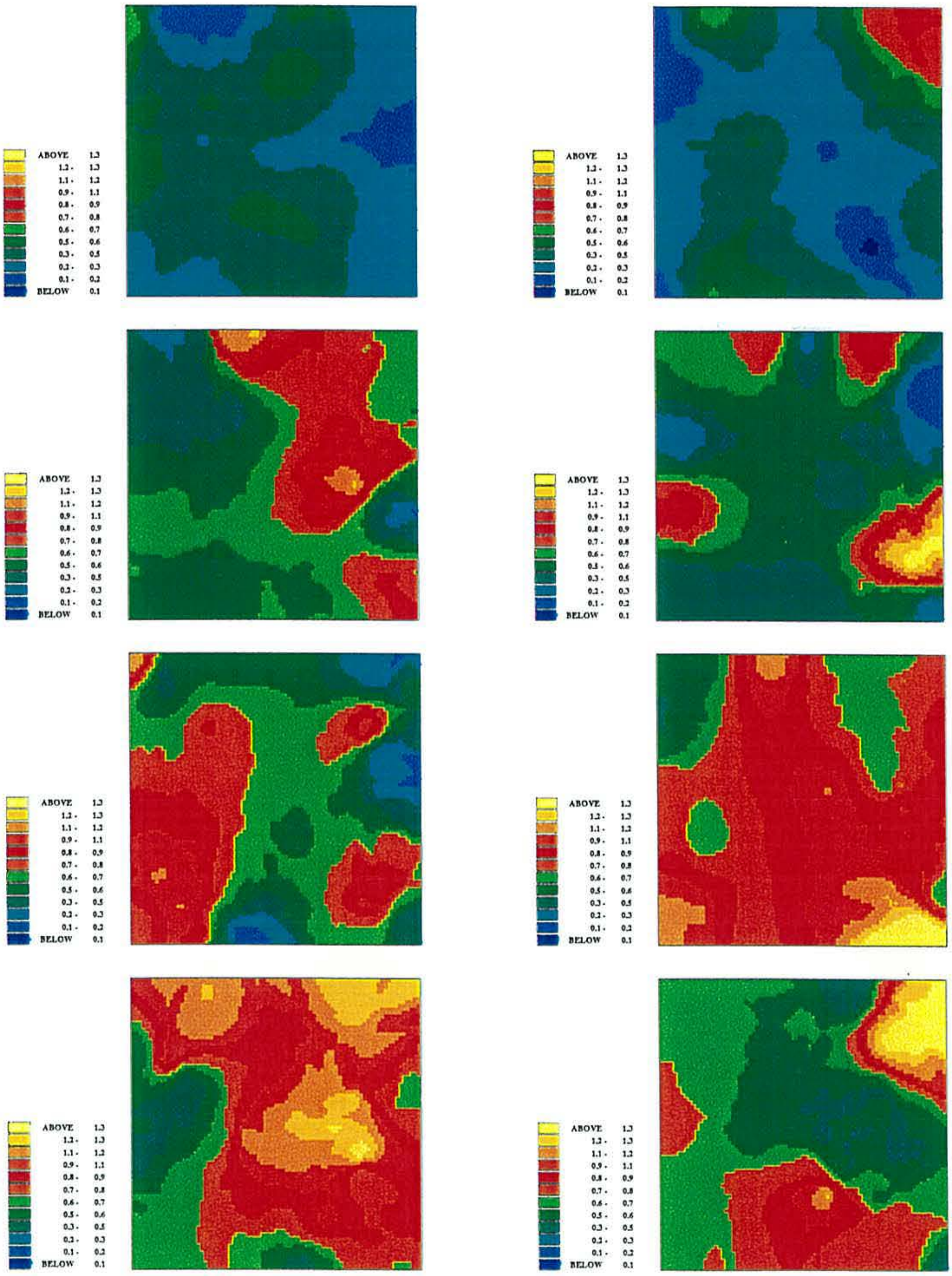


Figure 5.21 Total N content of surface soil samples

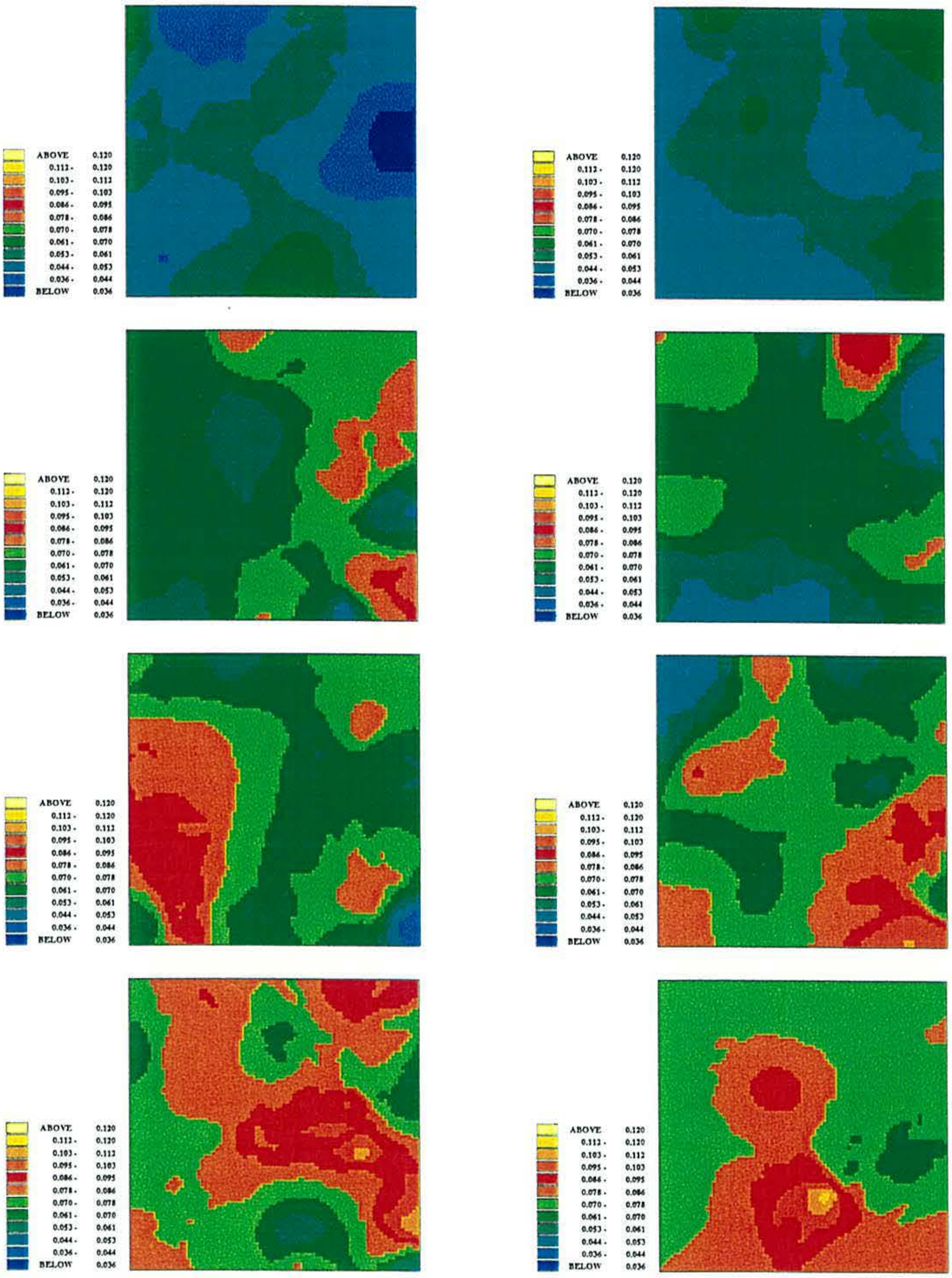


Figure 5.22 Total P content of surface soil samples

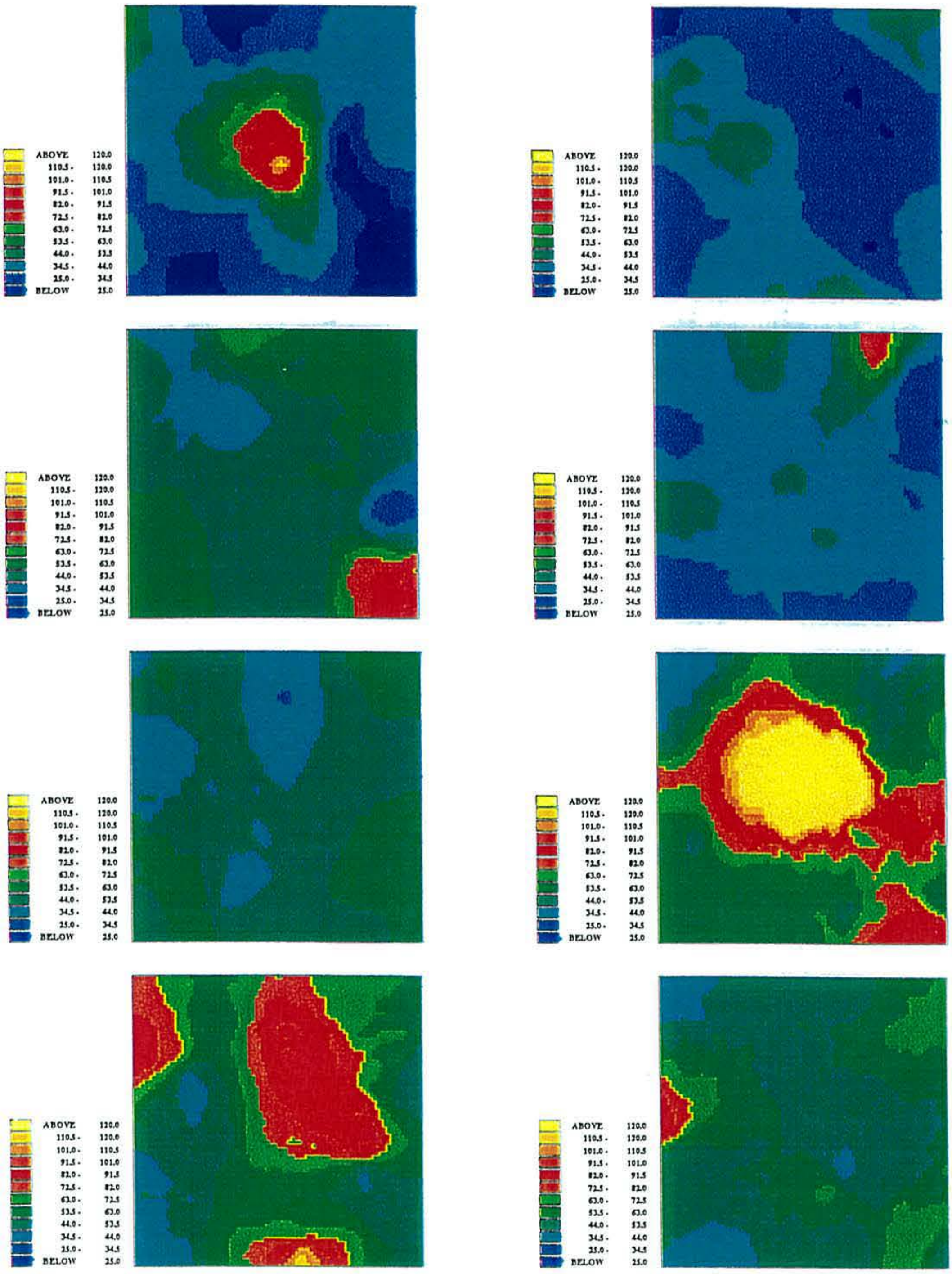


Figure 5.23 Organic matter content of surface soils

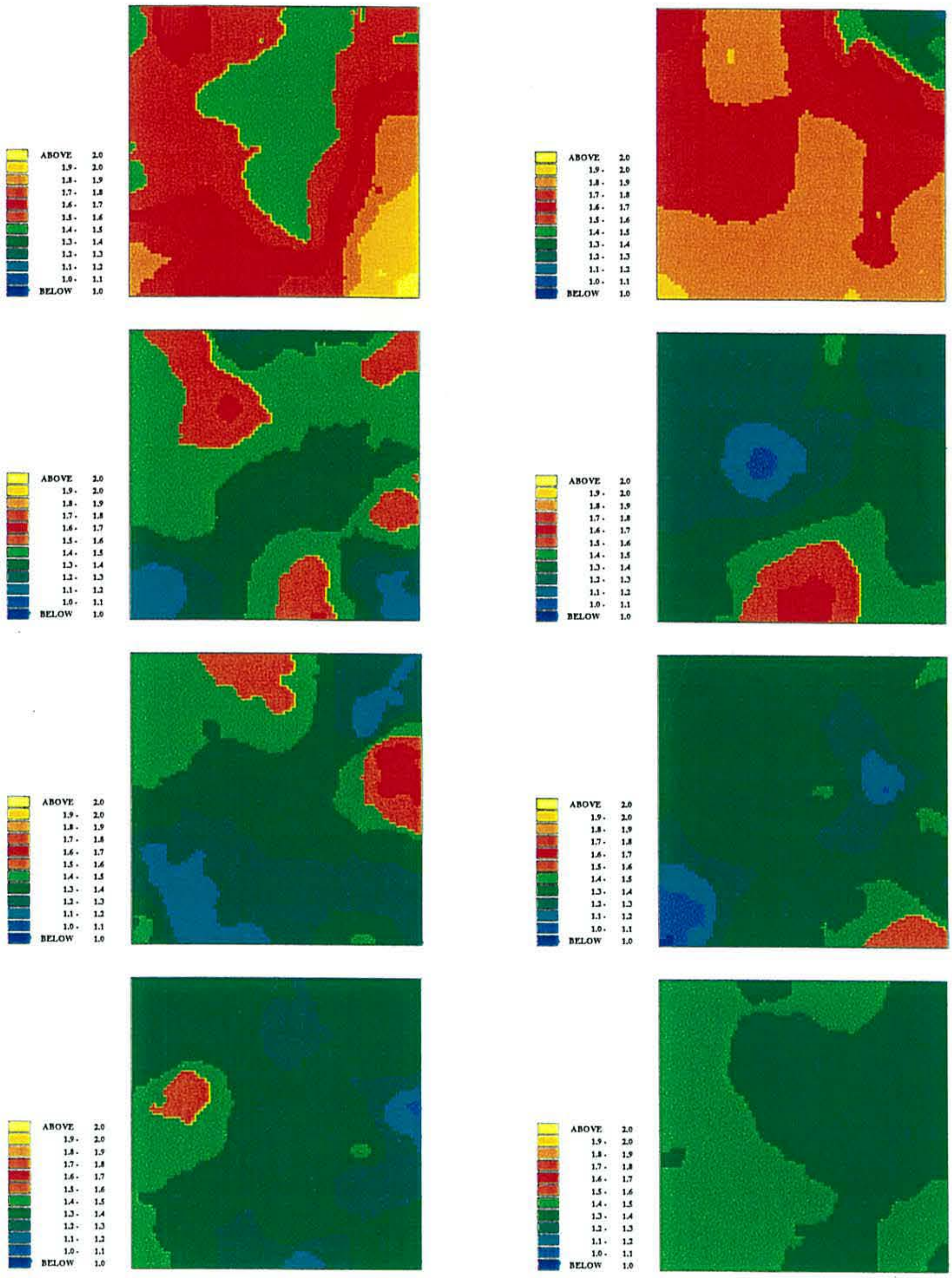
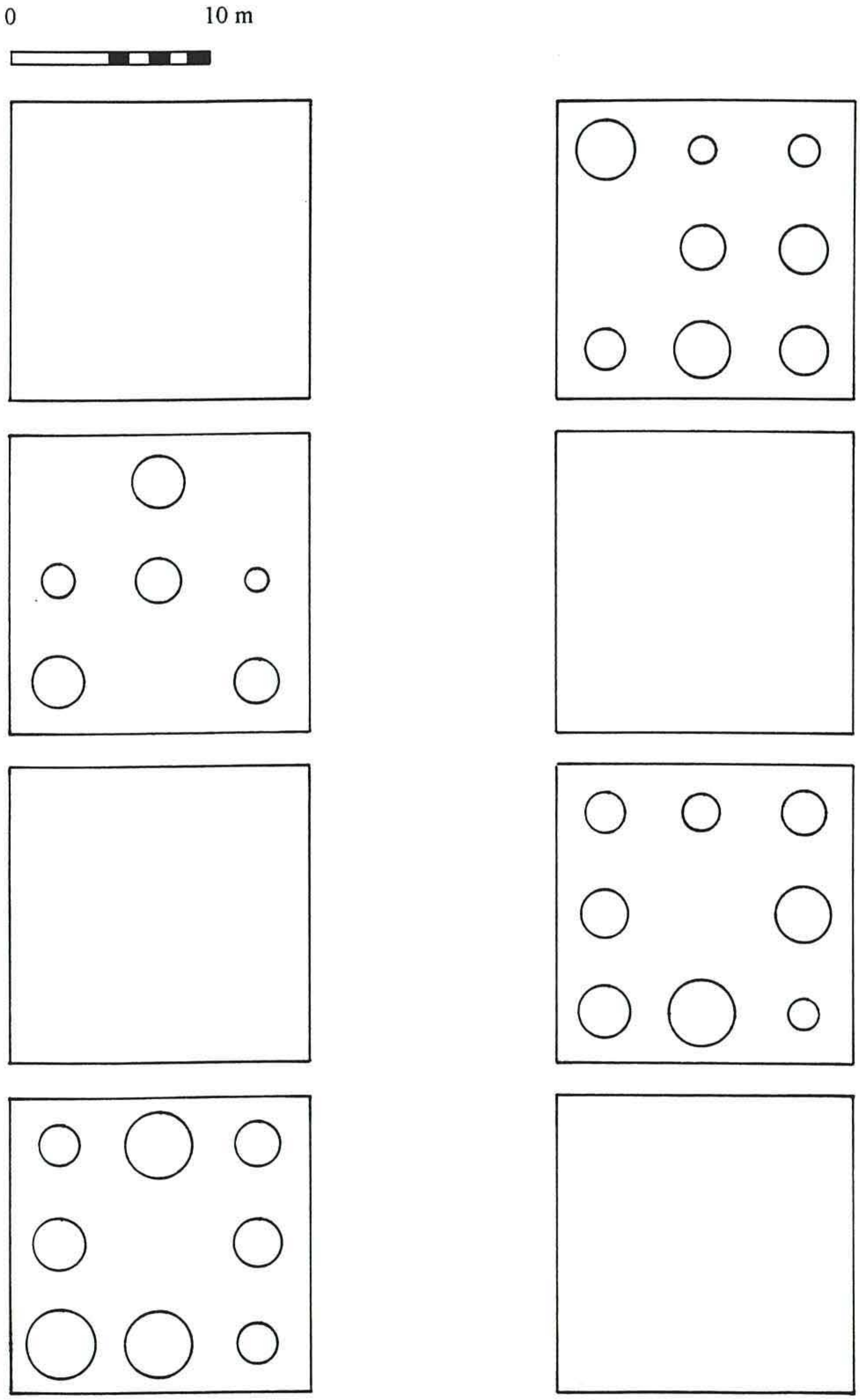


Figure 5.24 Tree canopy size overlay
(February 1994 - canopy measurements)



5.6 STATISTICAL PROCESSING

All statistical processing was undertaken using SAS/STAT and Base SAS with the semi-variances (section 5.6.4) plotted using SAS/Graph (SAS, 1991).

5.6.1 Tree plot *vs.* without-tree plot comparisons

In order to characterise the plots, compare plot differences with respect to the treatments applied and to examine spatial interactions between the soil variables and tree growth, the soil properties were analysed for differences attributable to the effect of trees by comparison between the tree plots and the control plots. Tables 5.2 and 5.3 respectively present these analyses for the surface (0-10 cm) and lower (10-50 cm) soil samples.

Table 5.2 Results of chemical and physical measurements on surface (0-10 cm) soil samples

	units	Plots without trees: no. of samples	mean	standard deviation	minimum value	maximum value	Plots with trees: no. of samples	mean	standard deviation	minimum value	maximum value	sed	(P<0.05)
Chemical													
pH (H_2O)		69	6.55	0.59	5.26	7.74	58	6.37	0.48	4.88	7.54	0.096	ns
pH ($CaCl_2$)		69	5.96	0.51	4.72	6.92	58	5.83	0.54	4.75	7.06	0.093	ns
Loss-on-ignition	%	61	2.57	2.22	0.39	11.55	57	2.72	1.41	0.67	6.09	0.345	ns
Gravimetric moisture content	%	68	10.21	4.70	2.17	22.97	58	9.34	4.36	2.48	21.48	0.813	ns
Organic matter	%	78	0.560	0.263	0.200	1.300	76	0.659	0.299	0.100	1.500	0.045	*
Total N	%	78	0.067	0.015	0.033	0.122	76	0.068	0.015	0.047	0.112	0.002	ns
Total P	$\mu g\ g^{-1}$	77	45.88	16.29	16.5	132	76	56.29	33.66	23.4	296	4.267	*
ExtractableP	$\mu g\ g^{-1}$	41	7.77	5.54	2.0	25.9	44	9.31	6.49	1.4	30.1	1.314	ns
EC (1:5)	$\mu S\ cm^{-1}$	71	63.27	22.99	29.8	123	68	62.29	21.64	28.2	123.1	3.791	ns
Physical													
Depth of sand layer	cm	28	14.34	22.40	0	65	28	18.33	24.21	0	72	6.233	ns
Penetration depth to 300 N cm^{-2} resistance	cm	78	13.70	10.41	1.5	50.5	78	12.87	8.70	0.5	37.0	1.536	ns
Penetration depth to 200 N cm^{-2} resistance	cm	78	10.82	9.41	1.0	50.0	79	10.49	7.70	0.5	42.0	1.371	ns
Penetration depth to 100 N cm^{-2} resistance	cm	78	7.00	6.94	0.0	43.0	79	6.47	5.30	0.0	25.5	0.984	ns
Topographic height	m	73	0.201	0.112	0.045	0.445	66	0.169	0.115	0.000	0.400	0.019	ns
Bulk density	gcm^{-3}	79	1.420	0.171	0.99	1.95	76	1.456	0.219	1.03	1.95	0.031	ns
Air-dry Colour Hue		63			7.5	7.5	57			5	7.5		
Value		63	5.48	0.67	5	7	57	5.51	0.71	5	7	0.126	ns
Chroma		63	6.32	1.15	4	8	57	6.11	0.88	4	8	0.188	ns

Table 5.3 Results of chemical and physical measurements on surface lower (10-50 cm) plot soil samples

		Plots without trees					Plots with trees						
	units	number of samples	mean	standard deviation	minimum value	maximum value	number of samples	mean	standard deviation	minimum value	maximum value	sed	(P<0.05)
Chemical													
pH (H20)		69	6.66	0.69	5.3	8.7	56	6.35	0.37	5.3	7.0	0.103	*
pH (CaCl2)		69	5.77	0.68	4.7	7.8	56	5.56	0.43	4.6	6.7	0.105	*
Physical													
Loss-on-ignition	%	60	2.41	1.23	0.47	5.09	57	2.78	1.41	0.47	8.01	0.245	ns
Gravimetric moisture content	%	68	11.67	6.60	1.9	45.2	57	11.55	5.53	2.31	23.62	1.102	ns
Air-dry Colour Hue		62			7.5	10	57			5	7.5		
Value		62	5.19	0.59	4	7	57	5.16	0.80	4	7	0.127	ns
Chroma		62	6.13	1.07	4	8	57	5.82	1.09	4	8	0.197	ns

Table 5.4 Correlation matrix of plot-level results

		Surface samples																	Lower samples				
		Topographic height	Bulk density	Depth of sand layer	Penetration depth to 300 N cm-2	Penetration depth to 200 N cm-2	Penetration depth to 100 N cm-2	Loss-on-ignition	Moisture content	Air-dry chroma	Air-dry value	Total N	Organic matter	Total P	Extractable P	pH [H2O]	pH [CaCl2]	Electrical conductivity	Loss-on-ignition	Moisture content	Air-dry chroma	Air-dry value	pH [H2O]
Surface soil samples	Bulk density	▲																					
	Depth of sand layer	▲▲▲	▲▲																				
	Penetration depth to 300 N cm-2	ns	▲	▲▲																			
	Penetration depth to 200 N cm-2	ns	ns	▲	▲▲▲																		
	Penetration depth to 100 N cm-2	ns	ns	▲▲	▲▲▲	▲▲▲																	
	Loss-on-ignition	▼	ns	▼	▼	ns	ns																
	Moisture content	▼▼	▼▼	▼	ns	ns	ns	ns															
	Air-dry chroma	ns	ns	ns	ns	ns	ns	ns	ns														
	Air-dry value	▲▲	▲	▲▲▲	▲	▲	▲▲	▼	▼	ns													
	Total N	▼▼	ns	▼▼	ns	ns	ns	ns	▲	ns	▼												
	Organic matter	▼	ns	▼	ns	ns	ns	ns	ns	ns	ns	▲▲											
	Total P	▼	ns	ns	ns	ns	ns	ns	ns	ns	ns	▲	▲										
	Extractable P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns									
	pH [H2O]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	▲								
	pH [CaCl2]	▲	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	▼	ns	▲▲							
	Electrical conductivity	ns	ns	▼	ns	ns	ns	▲▲	ns	ns	ns	▲▲	ns	ns	ns	▲	ns						
Lower soil samples	Loss-on-ignition	▼▼▼	▼▼	▼▼▼	▼▼	▼	▼▼	▲	▲	ns	▼▼▼	▲	ns	▲	ns	ns	▼	ns					
	Moisture content	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns				
	Air-dry chroma	▲	▲	▲	ns	ns	ns	ns	▼	▲	ns	ns	ns	ns	ns	ns	ns	ns	▼	ns			
	Air-dry value	▲	▲	▲▲	▲	ns	ns	ns	ns	ns	▲▲	ns	ns	ns	ns	ns	ns	ns	▼▼	ns	ns		
	pH [H2O]	ns	ns	▼	▼	ns	▼	ns	ns	ns	▼	ns	ns	ns	ns	▲	ns	▲	▲	ns	ns	ns	
	pH [CaCl2]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	▲▲

Key			n=24
Very highly positively correlated	P<0.05	r >0.8	▲▲▲
Highly positively correlated	P<0.05	0.60>r >0.8	▲▲
Positively correlated	P<0.05	0.404>r >0.6	▲
Very highly negatively correlated	P<0.05	r <-0.8	▼▼▼
Highly negatively correlated	P<0.05	-0.80<r <-0.60	▼▼
Negatively correlated	P<0.05	-0.60<r <-0.404	▼
Not significantly correlated	P>0.05	0.404>r >-0.404	ns

5.6.2 Characterisation of soils and soil inter-relationships

In order to compare the soil characteristics with one another, the results summarised in tables 5.2 and 5.3 have been correlated with one another and reported in the form of a series of correlation matrices. Table 5.4 shows a correlation matrix with all measurements for both the surface and lower horizons. Note that the Hue colour terms are not included in this correlation analysis since only two terms (10 YR and 7.5 YR) were measured. Since the samples examined for calcium carbonate content were selected from those with high pH values (pH ≥ 6.5) and not randomly selected, these results have also not been included in tables 5.2 and 5.3 or in the correlation matrix table 5.4. However, table 5.5 contrasts the results for this measurement from the surface (0-10 cm) and lower (10-50 cm) soil samples.

Table 5.5 Results of Calcimeter measurements

	Number of samples	Mean	Standard deviation	Maximum value	Minimum value
			% $CaCO_3$ equivalent		
Surface soil samples (0-10 cm)	20	1.16	1.41	6.01	0
Lower soil samples (10-50 cm)	20	1.19	0.77	1.69	0

5.6.3 Soil - Tree inter-relationships

The mapping of the soil measurements (figures 5.18 - 5.23) and of the measured tree growth function of canopy area (figure 5.24) allows for the projected canopy to be visually compared with the soil properties. Whilst there is no clear differentiation between the soils under and away from the canopy, it is possible that trends may be more subtle and requiring more detailed analysis of any possible associations between plant and soil measurements.

To examine associations between tree growth and soil properties at a smaller scale a series of analyses using the soil measurements as covariates in the analysis of the tree growth measurements has been performed. The soil samples in tree plots were each allocated to the tree nearest to the sampling position: where a sampling position was midway between two trees, it was allocated to the tree to the south and west of the position. All possible relationships between soil properties and tree height, mean crown radii and stem circumferences were then investigated using analysis of covariance, *i.e.* each soil measurement was used in turn as a covariate. None of the soil measurements were significant ($P.<0.05$) effects in the analysis of the tree growth functions. The effect of the presence of the sorghum intercrop was also tested but found not significant for any measured variable and, since it was not of primary interest in this study, is not discussed further.

Further analysis of the soil measurements has been performed. This has focused upon the relationship between bulk density and the penetration resistance since these can be considered to provide background information to soil structure measurements. Figure 5.25 illustrates the relationship between for these parameters. It is evident from figure 5.25 that there are linear relationships between the plot mean bulk density and the plot mean depth of penetration resistance measurements; these have been plotted using linear regression. In this figure there also appears to be a distinction between the tree (338, 364, 346, 372) and no tree (362, 340, 343, 348) plots. To test this visual impression, bulk density has been used as a covariate in an analysis of penetration resistance. The results of this are shown in Table 5.6. This shows that the depths of penetration resistance at 300 N cm^{-2} were significantly higher ($P<0.05$) in plots with trees than in those without.

Figure 5.25 **Plot of mean bulk density *vs.* mean penetration depth for 100 N cm^{-2}, 200 N cm^{-2} and 300 N cm^{-2} penetration resistance - additionally showing plot numbers and fitted linear regression lines**

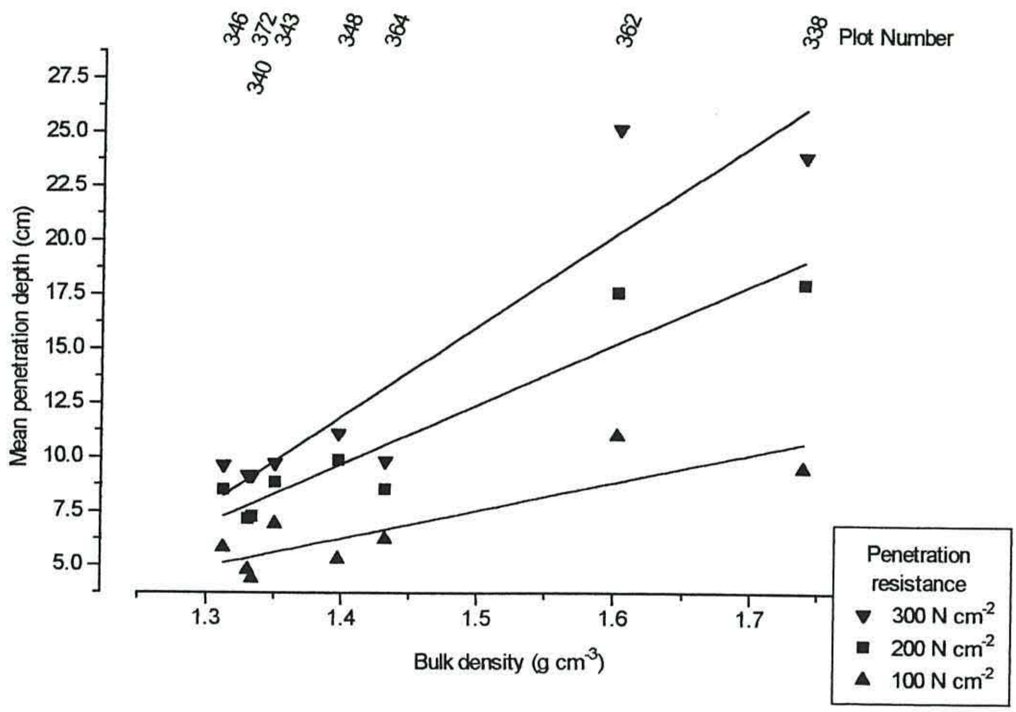


Table 5.6 Analysis of difference between tree and no tree plots for Penetration resistance with Bulk density included in analysis model

Measurement	Tree - no tree plot difference	t score	P value
Penetration resistance to 100 N/cm-3 ‡	-1.83	-1.08	P<0.40
Penetration resistance to 200 N/cm-3 ‡	-3.14	-2.78	P<0.10
Penetration resistance to 300 N/cm-3 ‡	-6.39	-4.43	P<0.05

‡ Analysis model: Crop*Tree + Bulk density (3 residual degrees of freedom)

5.6.4 Spatial analysis of soil measurements

The detection of trends due to the effect of trees against inherent variation in parent material has been approached by use of spatial statistical analysis. Semivariograms (Webster and McBratney, 1987) of the soil properties over lag distances from 1 m to 10 m have been made in order to examine the spatial variability at the intra-plot level. These are presented as a series of three semivariograms for each soil variable, (i) showing data from all eight plots; (ii) showing data from the plots without trees; (iii) showing data only from plots with trees. Figure 5.26 show these variograms. The variance and distance data of the semivariograms have been plotted in the same manner as in section 4.7, with an additional solid line. This line is a fitted spherical model (equation 5.1) (McBratney and Webster, 1986) of all the data (lag distances 1 - 21.2 m). This model was chosen since it is one of the most commonly used (*e.g.* Webster and Oliver, 1989) model of semivariograms and has an historical association with geostatistics from the work of Krige onwards. Further, more detailed, fitting and model selection (*e.g.* Webster and McBratney, 1989) was not performed because it was considered that little extra information would be gained; most of the variogram data in this instance appears diffuse at small lag distances.

Equation 5.1

$$\gamma(h) = \sigma^2 \{(3h/2r) - (h^3/2r^3)\}$$

for $h \leq r$

where h is the lag distance, $\gamma(h)$ the variance at lag distance h, r is the range and σ^2 is the sill (see figure 4.1)

Across all of the four planted plots, the mean crown radius of the trees is 1.02 m, therefore any effect of trees will be anticipated at similar small lag distances (see figure 4.1). Since there are fewer pairs of samples at these shorter (<2 m) distances the trend indicated by the fitted model, rather than by the data points alone, may be useful in spotting any effects due to trees.

Figure 5.26 Semivariograms of soils data at plot level

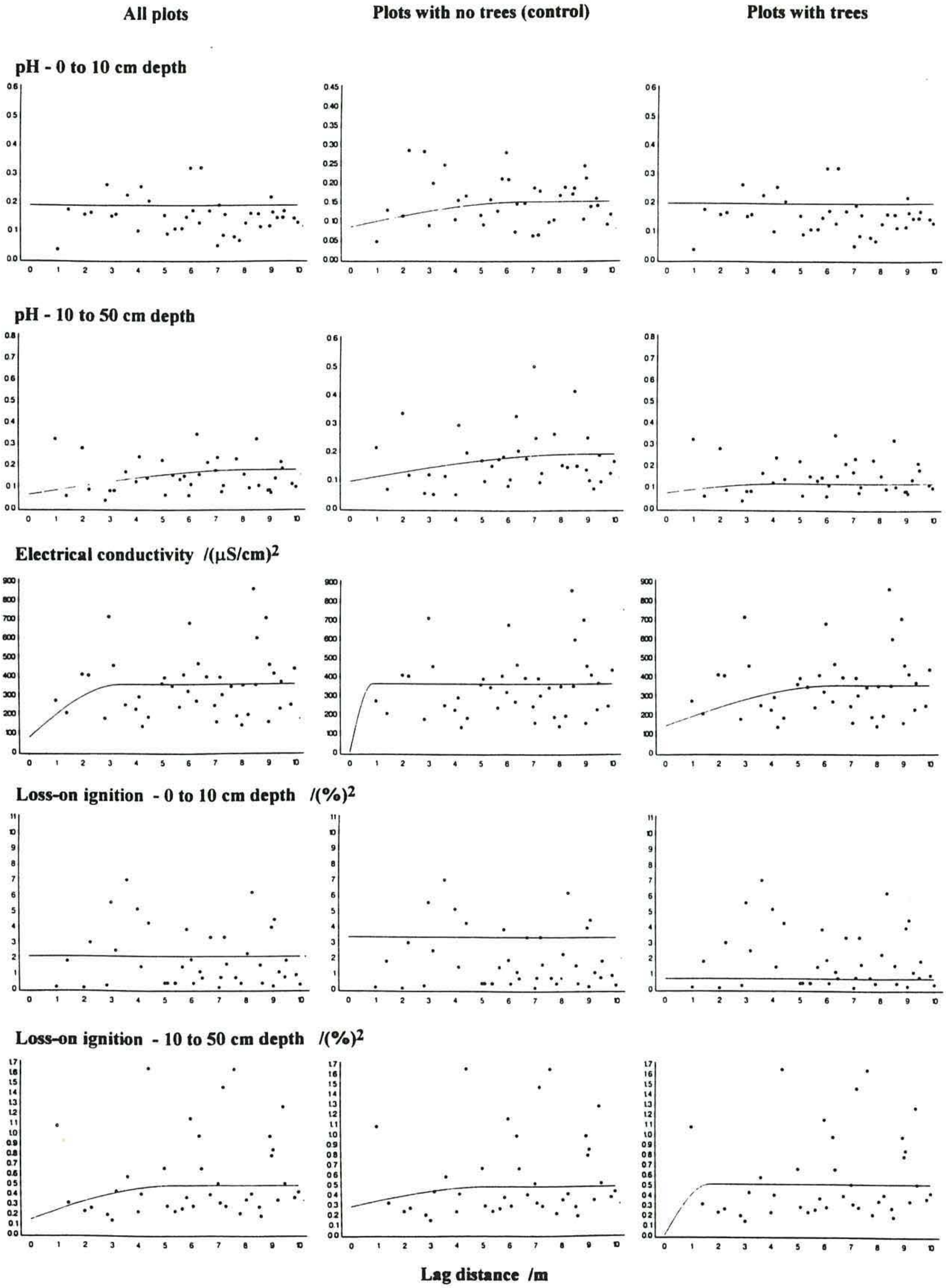


Figure 5.26 cont'd. Semivariograms of soils data at plot level

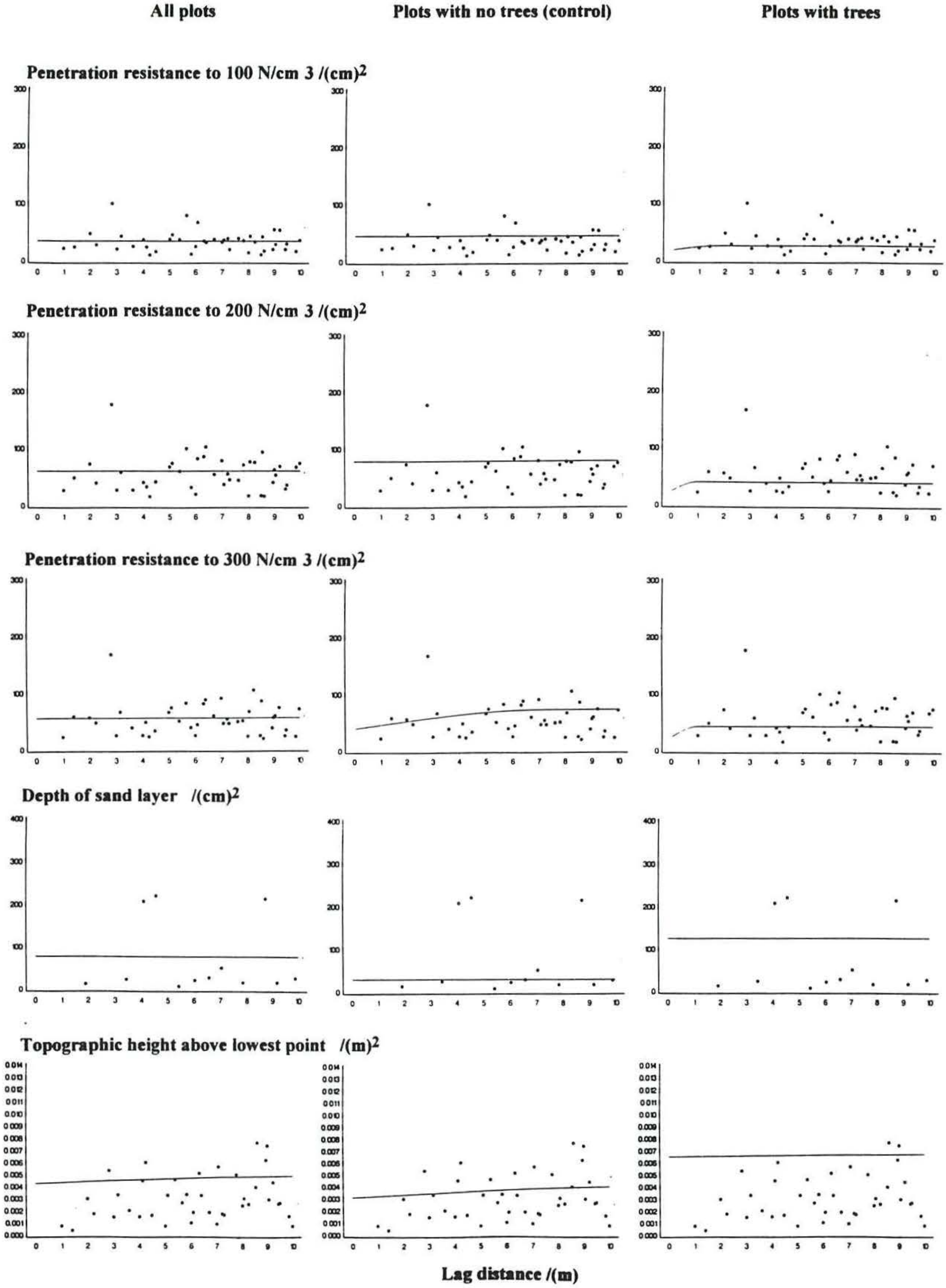
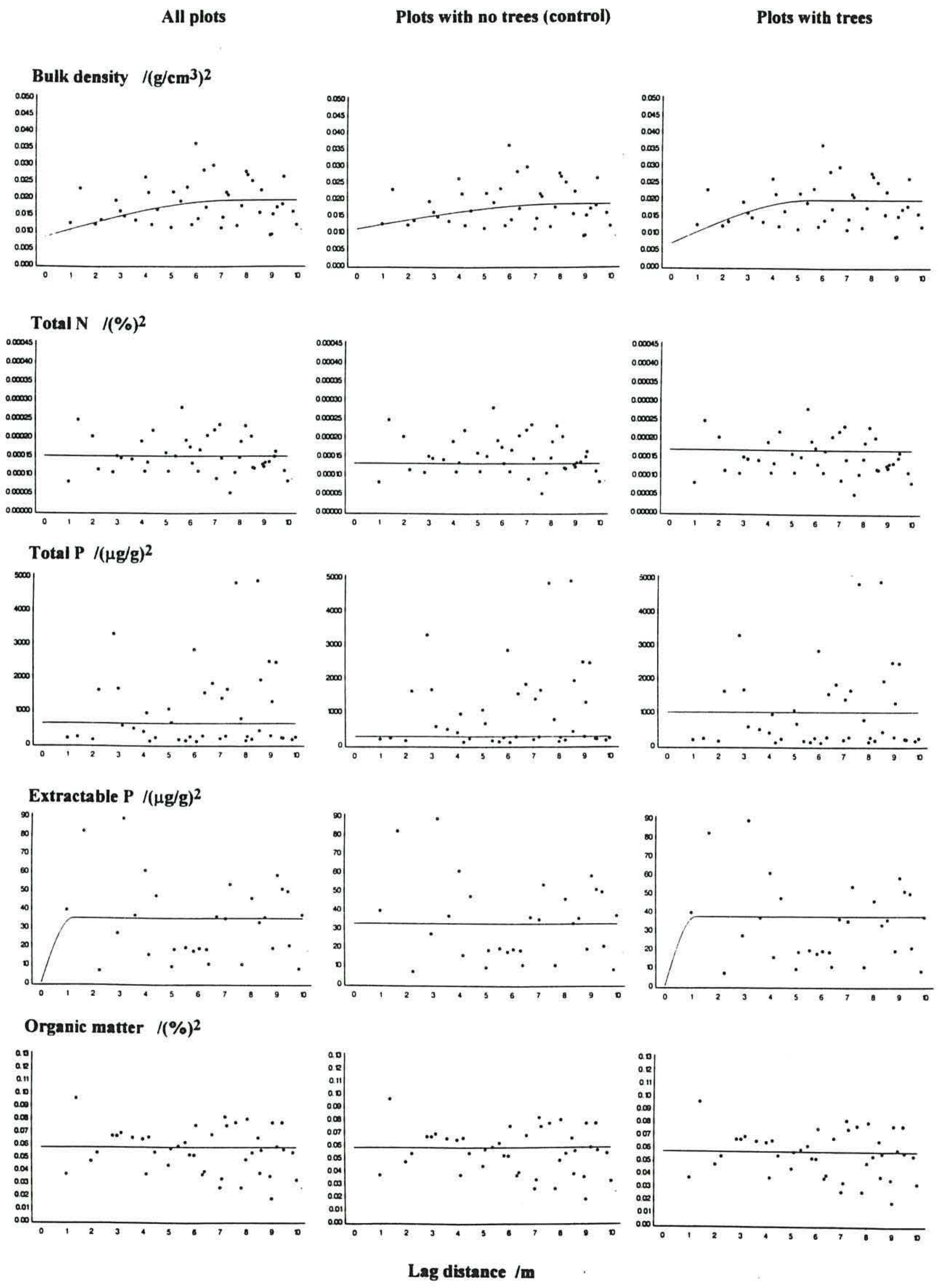


Figure 5.26 cont'd. Semivariograms of soils data at plot level



5.7 DISCUSSION AND CONCLUSIONS

5.7.1 Plant distribution

The dominance of the Gramineae is evident across both the sandy and clay-rich plots suggesting that they are the most adapted family for both these conditions. However, it is consistent that the single specimen of *Sida sp.* on the clay-rich plot 348 is a representative of the Malvaceae family which includes *Gossypium sp.* (cotton) and *Hibiscus sp.*. In this region, the Malvaceae are known to favour wetter conditions (White, 1983) as found on clay textured soils. It would be expected that the Leguminosae, with their ability to fix atmospheric nitrogen, would have a competitive advantage on nutrient-poor soils over other taxa. In this instance, however, the Leguminosae are distributed over both sandy and clay-rich plots, which would seem to indicate that the main factors in the distribution of these plants are their seed distribution and the localised soil moisture characteristics. Seed distribution will be dependent upon many factors including faunal excretion, wind and water transport. The mesh sides of the biomass boxes (Figure 5.17) may have intercepted wind blown plant material and seeds, but another likely cause of the two dominant species in the pairs of boxes 5 & 15 and 25 & 35 (Table 5.1) is the effect of the inundation of the site during the rainy season. This will both redistribute seeds, possibly marking "tide-lines" of selective seed redistribution and deposition as the waters advance and recede. Also there will be small but distinct differences (in 1994, 18 days difference between plots 362/338 and 372/348) in the timing of the exposure of these sites as the water ponding within the plots evaporated and drained away. This would certainly differentiate between species which benefit from the rapid drying on the sandy surfaces and those which prefer the slower drying, with possibly anoxic conditions, of the clay surface soils. It could be envisaged that these two factors, seed distribution and rapidity of drying, combined are the major influence in the distribution of plants found.

5.7.2 Field measurements

The microtopography measurements of the plots reveal (Figure 5.11) the distinct trend, visible in the field, from the higher sandy soils to lower lying clay soils (highest point in plot 362: 0.45 m above lowest point in plot 372), further reinforcing the view that the sand is an aeolian deposit upon the stratified lacustrine beds. The more detailed plot-by-plot mapping (Figure 5.10) reveals that there are considerable ranges in topographic height (minimum range found in plot 348: 0.07 m; maximum range found in plot 362: 0.33 m) within each plot. Since the maximum range is found in plot 362 with a distinct sandy surface, this implies both that the deposition of sand by aeolian processes is very localised and/or that there is considerable redistribution of this material, possibly by soil fauna. This small scale variability is in addition and possibly superimposed upon the variable surface topography of the aeolian deposits seen in Figures 4.4 and 4.15, where the depth of sand shows some long range (>25 m) linear "rippled" features. Again, (*cf.* Chapter 4) this indicates that the site has a mixed parentage offering considerable inherent variation to be overcome in comparative analyses between experimental treatments *i.e.* tree/no tree.

With still finer resolution these results may yield further information with respect to plant growth if corresponding measurements on the plants at this level are made. Such work would require alternative methods of examining microtopography at still smaller horizontal scales (*i.e.* <1m). Some methods for achieving this have recently been developed, the most common of these is the use of stereoscopic photographic examination techniques (Bergsma, 1992). However this technique is most suited to steep slopes where changes in microtopography due to erosion are linear and channelled, rather the flat level areas, such as that at New Marte where erosion processes are more evenly distributed over the surface.

Across all plots the relationship between the penetration resistance and the depth at which this resistance is met is linear, with increasing variability, as expressed in the standard deviation at depth (Table 5.2). Such results are consistent with other studies of soil strength and penetration resistance (Taylor *et al.*, 1966). The measurement of penetration resistance is dependent upon the moisture content of the soil at the time of sampling and the ability to replicate these measurements is dependent upon the user and procedure. Experimental factors which may affect the moisture content of the soil (*e.g.* tree water-use) appear to influence plot-to-plot comparisons (figures 5.14-5.16), but not significantly ($P<0.05$; Table 5.2). This possibly implies that any "tree effect" is masked by other physical factors such as the soil texture and bulk density (see section 5.7.4). Since the penetration measurements are dependent upon the user, sets of penetrometer measurements are not normally comparable from one experiment to another. In this set of results they are both comparable between plots, and can be usefully correlated (Table 5.4) with other measurements.

5.7.3 Characterising physical and chemical measurements

The inherent variability of the soils at the inter-plot (>25 m) level was demonstrated in the results of chapter 4. Likewise the mapping (figures 5.18-5.23) of the soil measurements at the plot level also shows this inherent variability. Since there is such variability and until the trees have been established for longer periods (20+ years), it is likely that the inter-relationships between the soil factors are as likely to be of similar importance to soil management decisions as any inter-relationships between the soils and the trees.

There are many significant ($P<0.05$) correlations amongst the soil measurement variables both within the surface soil samples and between these and the lower soil samples. The depth of the sand layer and the topographic height of the sampling position were, as expected, strongly correlated ($r=0.853$). The topographic height was also strongly correlated with the loss-on-ignition of the lower (10-50 cm) samples ($r=-0.851$) indicating the influence of the depth of the aeolian sand cover which will have a lower loss-on-ignition than the clay material since it contains smaller quantities of inherited organic material. Perhaps more surprisingly, topographic height was not correlated with the depth of penetration resistance measurements, although the depth of the sand layer was for all three forces measured. This indicates that the height measurements vary due to other factors (*e.g.* human and faunal disturbance, lateral water movement) in addition to the amount of aeolian material deposited.

The relative lightness of the surface soil colour (Munsell "Value" term) is positively correlated with topographic height ($r=0.691$), depth of sand layer ($r=0.821$), depths of penetration resistance, and with bulk density ($r=0.570$) of the surface soil. It is also negatively correlated with the loss-on-ignition of both the surface ($r=-0.524$) and lower soil samples ($r=-0.853$). Therefore this parameter would seem to be a good indicator of the clay content of the soil since all of these other parameters are related to the clay content.

There are fewer significant correlations amongst the chemical variables, presumably due to the very low values of the organic matter, Total N, Total P and extractable P, which were all approaching the limits of detection of the methods used. In these circumstances the distribution of the data is likely to be truncated, resulting in fewer correlations. While Total N and organic matter contents were related ($r=0.795$) with each other, neither was with loss-on-ignition. This would be expected because loss-on-ignition is additionally affected by dehydroxylation of the smectite clays (see section 3.3.2) and so varies with the clay content of the soil rather than with organic matter alone.

The results of the chemical analyses are comparable with previous work (Beavington, 1978) on samples taken from a soil profile similar to the clay-rich soils of plots 348 and 372. The results of all the variables in tables 5.2 and 5.3 are similar to this profile's results except for pH (H_2O) where Beavington found pH values of 7.9 and above. Like New Marte, the samples analysed by Beavington contained quantities of calcium carbonate ranging from 0 - 0.5 %, thereby suggesting more than one buffering system causing the high pH values that he found.

The ranges of extractable P and Total P values obtained (Table 5.2) were large due to the influence of small numbers of high values, in particular there is a feature in plot 340 (figure 5.22 - Total P measurements) which could possibly be due to a below-ground termite structure. The range over all the plots of the extractable P values is from 2.0 - 30.1, which is nearly the full extent of the measurement range (2.0 - 40.0 $\mu g\ g^{-1}$) of the method used. The Olsen method of extraction is also subject to variations in the soil pH (Landon, 1991), and it has been reported (Hesse, 1971) that drying of samples will decrease the extractable P on high pH soils. The ratio between total P and extractable P contents is therefore very variable (mean: 4.8; max.: 36; min.: <1; standard deviation 6.9). In more humid tropical (Landon, 1991) and in temperate soils the ratio between these is often much greater (>10).

5.7.4 Soil measurements with respect to tree planting at New Marte

While it has been shown in chapter 4 that tree survival on this site was affected by inherited soil properties at the larger inter-plot scale (>25 m), there is no evidence, from the covariate analyses, of a relationship between the tree biomass measurements and any soil property at the intra-plot scale considered throughout this chapter (tree - soil nutrient relationships are discussed in chapter 8). The inherited variability of the soils over (1-10 m) is graphically illustrated in the semivariograms. At this range of distances the soils may also be revealing patterns inherited from the long removed but possibly long established trees which form the past vegetation of the site. Despite this inherited variability, the analysis of the plot means reveals that two chemical properties (Total P, Organic matter) in the surface soil are significantly higher in the plots with trees (Table 5.2). Whilst the effect of biomass inputs from the trees is shown in the organic matter measurements, this is not mirrored in the loss-on-ignition, presumably due to higher values for this variate being found in the more clay rich plots to the south of the site (see section 4.6) resulting from inherited organic matter in the lacustrine deposits and dehydroxylation of clays, with the effect of this inheritance being greater than any effect of organic inputs derived from the trees.

The pH measurements of the lower soil samples (10-50 cm) are significantly ($P<0.05$) lower in the tree plots (Table 5.3), A variety of possible explanations could be constructed including the effects of tree root exudates and increased water movement and soil drying due to trees which would induce reduced deposition of calcium carbonate at increased depths.

No significant ($P<0.05$) differences between the plots with and without trees were found for the physical parameters (Tables 5.2 and 5.3). Similarly when the semivariograms of the physical properties are examined there are no distinct trends or relationships to trees evident at any distance between sampling points. The effects of trees would be anticipated to become apparent within the mean canopy radius (<1.03 m). Plots with trees did, however, have a significantly higher mean resistance to penetration at 300 N cm^{-2} than plots without trees when underlying differences in bulk density were taken into account. This could be caused by the physical presence of tree roots impeding penetration, or a result of soil in plots with trees drying out more quickly as a consequence of water uptake by tree roots, leading to increased soil strength and hence increased penetration resistance. The latter situation is considered more likely since the differences between the tree treatment for penetration resistance at the other two resistance force values (100 N/cm^2 and 200 N/cm^2) are not significant, as would be expected if direct physical interference by roots were the cause.

The relationship (figure 5.25) between higher bulk density and greater depths to reach a specific penetration resistance is surprising since the penetration resistance would normally be expected to increase as the bulk density increases. As is illustrated in Figure 5.34, the greatest bulk density is found on the massive structured sandy-surface soils of the northernmost plots (338 and 362), whereas the clay-surface soils are more strongly structured and have much greater porosity (see chapter 6), due to cracking and/or the activities of meso-fauna; hence they have smaller values of bulk density. Since there is an effect of moisture content on the soil strength and the friction created by different soil particles, it would be expected that the penetration resistance would increase as the soil dries. Ahmad and Paul (1978) have reported drying in conjunction with a distinct decrease in root extension of sugar cane plants in a vertisolic soil when the soil penetration resistance exceeds 100 Ncm^{-2}.

There was no evidence in the semivariograms for a reduction in the variability of soil properties from samples taken closer to each other than those from positions further apart in the plots (*i.e.* neither situation A or B; Figure 4.1). It is also evident from the mapping of the variables (Figures 5.18-5.23) that small-scale spatial variation in all the variables measured was high, there were neither clear spatial trends across plots nor evidence from the semivariograms (Figure 5.26) of distances over which soil became significantly more homogeneous with respect to any of the variables measured in either the plots with trees or those without. This would indicate that the scale at which heterogeneity is experienced on these soils generally, is expressed at even smaller (*i.e.* 10 cm and less) levels than that examined at this intra-plot level (1-25 m). This is consistent with the short-range (1 m) measurements of Scott-Wendt *et al.* (1988) in a similar Sahelian land system. Since there was no detectable effect in the semivariograms of the presence of trees at a plot level on the same variables, it is reasonable to assume that much of the variability is inherent rather than caused by the trees. Given such high initial variation, it will require longer than the six years after tree planting for more pronounced effects to become apparent.

5.8 CONCLUSIONS WITH RESPECT TO AGROFORESTRY AND FARMING LAND USES

There are important implications of the small-scale (1-10 m) spatial variability shown in the semivariograms, regardless of whether this variability is inherited or acquired, both in terms of farming strategies and agroforestry experimentation. As discussed by Brouwer *et al.*, (1992), there is a need for subsistence farmers to exploit available land areas with such variable soil properties in poor rainfall years. This provides the farmer with a wide range of site conditions, where at least some should support a crop to harvest. This approach on the micro-scale reflects the more general social issues addressed by Mortimore, (1989) where multi-practice agriculture and land-use is used as a survival tool in periods of drought. Lamers *et al.*, (1995) details several possible management practices suitable for the Sahelian farmer, including use of traditional bush-fallow periods but with particular emphasis placed upon the management of organic materials through translocation, animal manuring and incorporation of crop residues. Such practices are the basic tenets of the Tropical Soil Biology and Fertility programme (Anderson and Ingram, 1993). In the Sahelian region it is known that farmers recognise such soil microvariability and adapt their practices accordingly, for example in deliberately applying high concentrations of organic material such as plant residues to small areas or by kraaling animals in order to use their manure on a specific area (Chase & Boudouresque, 1987). Lamers *et al.*, (1995) state that farmers also recognise differences in soil fertility associated with their proximity to trees, with some species thought to have negative effects and to diminish crop growth and others including *Acacia (Faidherbia) albida* positive effects.

The most direct implication in terms of the agroforestry system studied is that the experimentation is superimposed upon an area which already displays spatial horizontal heterogeneity at both large (25 m) and small (1 m) scales, confounding an inherently high variability in the plant and soil responses. This is a problem common to many agronomic experiments outside of controlled environments and, to try and counter this, increasingly powerful geostatistical methods are being used and developed (McBratney, 1992). In the overall experiment at this site, a major interest is in the "niche differentiation" between the trees and the sorghum plants. The small scale variability examined in this chapter, is therefore perhaps best countered with comparisons over plots rather than at the level of individual trees.

Agroforestry experiments such as this, which impose a regular design (figure 1.18) on horizontally variable soils, do not mimic either the planting positions which would be adopted by local farmers or the naturally occurring locations of regeneration if the area was protected from tree removal. It may therefore be considered more effective to study soil and plant responses around pre-existing trees (*i.e.* not specially planted for an experiment) in the manner of, for example, Lindley and Deans (1992) and Gerakis and Tsangariakis (1970) or to identify soils which would be chosen by local farmers for tree planting and then design tree and intercrop studies around these areas.

A factor which has been identified by Sanchez (1987) as limiting research on soil amelioration by trees, is that trees tend to be favoured on some soil conditions rather than others thus limiting the possibility of identifying the effects of trees on the soil. Young (1989), highlights the tendency when designing agroforestry systems to plant trees in nutrient-poor areas, thereby diminishing their potential to ameliorate soils. These two comments imply that the farmer or agroforestry scientist needs to identify soil niches before planting trees for agroforestry, as well as considering different tree and crop species. In this experiment at this intra-plot level there were no soil factors significant as covariates in the analyses of the tree biomass factors, suggesting that the inherent variability is too great to identify soils favoured for tree growth. Whilst still smaller-scale measurements may be considered, it can be concluded from the variograms that the soil is as variable over distances of 1 m as it is over distances of 20 m.

The differences in the mean variables between the plots with trees and those without suggests that trees are having some effect in soil processes and these effects are starting to become evident over the inherent variability of these soils. It would be therefore sensible to predict that further and more pronounced effects due to trees will become apparent after the necessarily longer periods of tree growth.

6 Soil structural characteristics

6.1 INTRODUCTION

At the New Marte experimental site a wide range of surface soil textures have been found in both the site-level and plot-level measurements (see sections 4.4 and 5.3). The soil structure so far developed, and any detectable modifications found after tree planting, are the subjects focused upon in this chapter. These studies form the core of the overall hypothesis of the agroforestry experimentation at New Marte as it relates to soil issues. This chapter specifically examines the plot experimentation at New Marte using techniques designed to investigate soil structural differences at a level, termed meso-structure, where changes, either development or degradation, have their greatest influence on water infiltration.

6.1.1 Hypothesis of soil structure research

The central part of the overall experimental hypothesis for the agroforestry experimentation taking place at New Marte, converges upon the rôle of the structure of the soil which in turn will influence water infiltration. Two specific hypotheses (see section 1.3.2) relate to this work:

A. Tree biomass inputs and rooting activity improve soil structure.

B. The improvement in soil structure (*cf. A*) leads to increased infiltration and penetration of water, and, therefore increased water available for use by trees and crops.

In order to assess any changes that have occurred and may be identifiable due to the influence of trees on the soil structure and to assess directly water infiltration, a variety of comparative evaluations and experiments have been performed at New Marte and upon soil samples brought back to the UK. This chapter considers only the first two factors in the sequence where soil structure influences water infiltration which alters the overall water regime, which in turn influences tree and crop growth.

In order to address the hypotheses, three groups of experiments have been undertaken: (i) a quantitative assessment of soil structure at a level (termed meso-structure, in the order of 10^{-1} m to 10^{-3} m) of scale where the chemical effects of tree inputs, biological effects of soil meso-fauna (a major factor in the cycling of organic material) and direct physical effects due to the presence of trees will be most evident. (ii) experimental testing of the stability of soil aggregates when subjected to stresses imposed by water. (iii) examination of water infiltration in relation to surface structure. This chapter considers (i) and (ii), whereas water infiltration (iii) is the subject of chapter 7.

6.1.2 The importance of soil structure

Soil structure is a term that has attracted many different definitions by various authors, these definitions have tended to accommodate the issue or factor being addressed (*e.g.* biological), or specifically exclude another, rather than be generally applicable. This slight confusion arises often when a distinction is made between the factors influencing soil structure development; for instance, separating biotic from purely physical phenomena. In any attempt to define soil structure, there is an ontological problem in that soil must also be defined. Although many definitions of soil have been put forward there is a general agreement that soil must exhibit development from a parent material. Jenny (1941) distinguished between parent material and soil on the basis of soil being anisotropic (varying in different directions) at a macro-scale whereas parent material at the same scale is isotropic. A major physical feature of a soil is therefore the physical arrangement of the materials that the soil comprises. This serves as one definition of soil structure and is shared by Baver *et al.*, (1972). A more explicit, and somewhat pedantically, stated definition is that by Brewer (1964), which includes the concept of arrangement of soil particles thus:

> "The physical constitution of a soil material is expressed by the size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles, and the compound particles themselves; fabric is the element of structure which deals with arrangement".
> (Brewer, 1964; page 132)

This definition is adopted in this thesis and has also been commonly used elsewhere (*e.g.* Letey, 1991). The importance of this definition lies in that it separates and distinguishes between the terms "fabric", "structure" and "arrangement" which had at times previously been used in various amalgams - *e.g.* Jacks's "soil architecture" (Jacks, 1954). In summary, soil structure is considered an important soil property and although not necessarily varying independently of other soil properties (*e.g.* organic matter content) it is seen to be a key indicator in the progression from parent material to a soil.

In the context of the Chad Basin, the development of soils is limited to the period of exposure since the last recession of the lake, but as has been discussed (section 2.3.3), there is very little knowledge on the distribution of Lake Chad in antiquity or at any other point in the Holocene. Reports of excavations at various archaeological sites, (*e.g.* Connah, 1981; Breunig *et al.*, 1993) have not included any detailed structural descriptions of either disturbed or natural soil profiles.

In assessing the differences in the structure of the soils at the New Marte site, the examination of the chronosequence described in chapters 2 and 3 can show, in terms of various structural parameters, where the soils at the New Marte site are coming from and going to. Furthermore, by drawing these two aspects together, this may allow for the boundaries where changes in sedimentary exposure occur within the Chad Basin to be more precisely ascribed.

6.1.3 Soil Structural observations

Despite Brewer's precise definition of soil structure given above, the study of soil structure is perhaps made more difficult by the inclusion of the term "arrangement". Soil structure is then a soil property to which it is very difficult to assign quantitative descriptions. Measurements that may have been seen to act as a surrogate for such a quantitative description, for example bulk density, provide no indication of the arrangement of soil particles. Soil structure is still predominantly described in terms of field characteristics using standard terms of reference, such as those of Clarke (1971) and Hodgson (1976), rather than from laboratory measurement. However, with the increasingly recognised importance of soil structure, particularly where soil degradation is occurring (Hamblin, 1991), there has been an increased effort to develop robust quantitative methods in order to quantify structure.

This demand for numerical data of soil structural characteristics is particularly noticeable with the increased use of computer modelling of land uses, for instance: the "erodibility factors" (the *K* factor) within the USLE model (Wischmeier and Smith, 1960; DeMeester and Jungerius, 1978) in the USA; the PERFECT model (Littleboy *et al.*, 1989, reviewed by Coughlan *et al.*, 1991) in Australia and the SCUAF model (Young and Muraya, 1990) in East Africa. Whilst the first two of these models operate at very large scales (km^2), and the third at a slightly smaller scale (m^2), there is also an increasing demand for information at much smaller scales (cm^2)

for a variety of disciplines: root dynamics (*e.g.* Smucker, 1993); gaseous exchange in soils, first described requiring soil structural information by Currie (1960a; 1960b); and soil microflora (*e.g.* Wright *et al.*, 1993).

Lately, fractal geometry, developed from a branch of Hilbert mathematics and popularised by Mandelbrot (1977), has been used to describe soil structure. One of the most important features of fractal geometry is that, with certain criteria, it displays self-similarity at different orders of scale; a feature which Mandelbrot, perhaps confusingly, calls "scaling" (Regis, 1989). Because of this, fractal geometry can be used to address the shape and topology of surfaces at a variety of scales from the microscopic (*e.g.* Crawford *et al.*, 1993) to regional landforms (*e.g.* Barnsley, 1993). It is increasingly being used as a representation of soil structure in order to assess and model other soil parameters such as water retention (Bird *et al.*, 1996). Another important aspect of fractal geometry in the context of soil structure, is that fractal descriptions may be applied to either the shape of aggregates (Young and Crawford, 1991; Rasiah, *et al.*, 1995) or, alternatively, to the shape of pores (Kampichler and Hauser, 1993).

6.1.4 Methods developed for measuring soil structural features

Whilst fractal geometry may provide a different descriptive element to soil structure assessments, and may prove to be a powerful tool for modelling, it still relies on measurements of soil structure for a reference basis. Other systems of description all have different demands of soil structure measurements. Many different methods have been developed to attempt to quantify aspects of soil structure. These may be relatively simple, such as bulk density estimations by gravimetric measurement indicating the total porosity of the soil (Hodgson and MacLeod, 1989), or complex such as pore size distribution given by mercury porosimetry (Diamond, 1970). As another contrast, some methods treat soil as an engineering entity and measure shear strength or plasticity limits (Atterberg tests) (Baver *et al.*, 1972), still others measure a property which is known to directly relate to structure such as ponded (Collis-George, 1980) or unsaturated infiltration and other transport phenomena (Mott *et al.*, 1979). The use of a surrogate, as in the last examples, can be extrapolated further, for instance, to measurements of water turbidity in river catchments associated with a particular soil type and area (Hamblin, 1991).

Whilst the techniques mentioned so far may allow a specific rôle of soil structure to be assessed, none of them provide any information to the arrangement of the soil particles. Pore size distribution estimates by mercury porosimetry may give very detailed information on the sizes of pores, but do not produce any information on their tortuosity or orientation. Whatever technique is used for measuring soil structure it will have specific limitations, in addition to those normally encountered of sampling error and measurement precision. Therefore, in selecting methods to attempt to quantify soil structural properties, the potential use of any results gained must be considered. This factor is particularly important in experimental situations involving plant responses where many methods are completely insensitive to changes due to plant growth (Letey, 1985).

It appears therefore, that some form of visual assessment of soil structure from a soil cross-section is needed. For any kind of useful quantification from visual observations, the objects seen (pores, aggregates, root channels, *etc.*,) will need to be analysed for size, shape and orientation. These data can be found either for individual objects or as summary data for a particular class of objects and can then be compared and analysed in a number of different ways.

In this thesis, the measurements of soil structural properties are trying to achieve two distinct aims, one is to examine long term differences (kyrs) at the regional level of the soil chronosequence; the second (the subject of this chapter) is to examine changes at the experimental plot level where both physical and biological components are of major concern, the latter including floral (root action, biomass input) and faunal (termites) influences.

The experimental approach undertaken has been two pronged. First, a series of soil samples have been collected *in situ*; representing the surface state of the soils at New Marte during the dry season. Sections of these soil samples have been made and the size and shape characteristics quantitatively analysed. The images of these sections and these data have then been described by different techniques. These experimental procedures are described and discussed in this chapter. Secondly, this visual information has been augmented by other information including routine examination of the micromorphology of the chronosequence profiles and also information relating to properties of the individual aggregates (aggregate stability) and to properties of the bulk soil (infiltration measurements). These last two topics are discussed in Chapters 3 and 7 respectively. Both the plot experimentation and the measurements from regional samples have tried to consider field conditions of the soil at the onset of the rainy season in Northern Nigeria.

6.1.5 Plot locations at New Marte

The soil structure measurements have been performed on the plots allocated to the 1988 year of planting in block 4. These plots are the same as those used in the majority of the other plot experimentation (see chapter 5) and are shown with the experimental treatments applied in figure 5.1.

Two randomly selected positions in each of the eight plots were sampled. In the plots with trees, the positions relative to the trees were kept to a fixed radial distance of 1.5 m. In the control plots the sampling positions were at the nodes of a 1 m grid. Therefore a total of 16 sampling positions were allocated. The plots were sampled during February/March 1994, more than four months after the last rainfall. The rainy season of 1993 was particularly poor and the sorghum crop failed. Any sorghum residues had been removed/decayed in November 1993 and were not noticeably evident in February 1994. Therefore the effect of the sorghum is discounted, because of both the poor performance of the sorghum crop and because samples have been taken in positions with minimal influence from the sorghum cropping activities. The ground surface cover at the time of sampling comprised of termite deposits and dried-up weeds.

6.2 IMAGE ANALYSIS

6.2.1 Relationship with other measurements

In order to try and quantify the soil mesostructure, of which the pore space is a major factor, a technique employing the impregnation of soil blocks *in situ* and image analysis of their cut section has been undertaken. In this instance, the differences between plots containing *A. nilotica* and their associated control plots are being sought. In order to achieve this, account must also be taken of the differences between the soils due to their varying texture. In the clay-rich soils it is expected that large scale polygonal cracking may be apparent at several levels of magnitude whereas the sand-rich soils may not show such cracks.

6.2.2 Previous work on image analysis of soil sections

The study of structure from two dimensional soil sections has developed from a purely descriptive standing to the point where quantitative measurement of the spatial arrangement of soil particles can be achieved through image analysis. The use of point counting techniques is long established and was the amongst the first methods to be adapted to computer-based scanning and calculation (*e.g.* Dexter, 1976; Dexter, 1991). The development of a procedure involving the digitization and quantitative processing of soil sections was first conducted in 1966 using Quantimet equipment, a unit which closely integrated the hardware (a series of array processors) and software (Jongerius *et al.*, 1972). Unfortunately the then standardised micromorphometric technology developed for the Quantimet B is no longer available, requiring the development of alternative techniques. These have shown a trend of increasing separation between hardware and software, leading to wider availability of image processing techniques since much of the software produced can now be used on standard personal computers rather than on dedicated equipment. This increase in availability has meant that many more publications within the realm of image processing of soil sections have been produced, raising fears that some of the work is using misguided or faulty techniques (Thompson *et al.*, 1992). Of particular concern is the introduction of artefacts which can occur at almost all stages of the technique from sampling through to the final quantitative analyses. In common with many soil science methodologies, there is currently no established standard method of procedure. Numerous procedures have been proposed and some have become adopted more frequently than others (Protz *et al.*, 1987). This means, therefore, that there is no ready way of assessing the precision and accuracy of any one particular set of results in comparison with other sets of results gained by a different method.

Many papers have been produced in the last two decades on image analysis of soil sections at the microscopic scale (*e.g.* Bullock *et al.*, 1985) and recently there has also been an increase in its use at larger sizes of sectioning. Protz *et al.*, (1987) whilst relating the concept of a pixel from global level image analysis down to sub-microscopy, used the term "macrostructure" to describe soil structural features which expressed themselves in the range of 10^{-1} m to 10^{-2} m. For these vertisolic soils, the term "meso-structure" has been adopted to describe this category, since very large scale structural features (here termed macro-structure) may have a spatial periodicity of a few metres, such as the deep cracking found in a vertisol, and hence fall outside the sampling regime adopted.

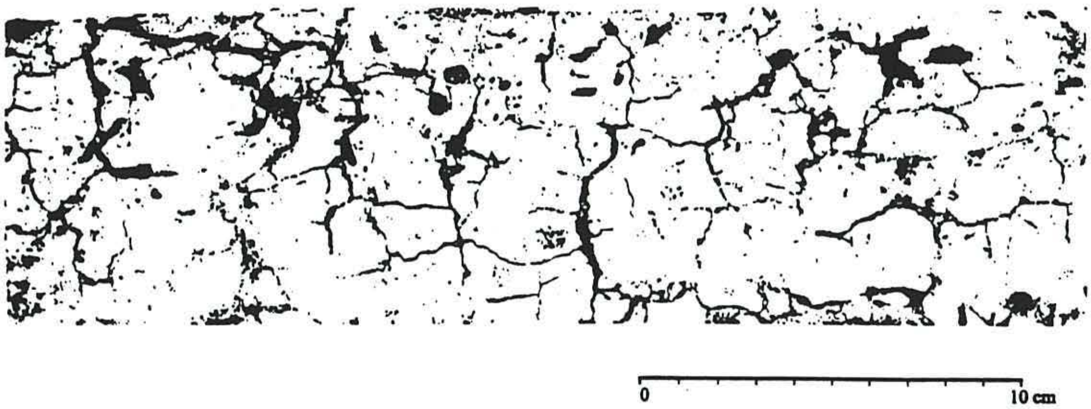
Most methods have been borne of circumstance, particularly for the initial field sampling. The conditions in which soil structure samples have been taken has varied from wet temperate (*e.g.* Fitzpatrick 1984) through to arid conditions (*e.g.* Puentes & Wilding, 1990). Similarly, the range of soil fabrics has encompassed all types. The differences in the sample taken and its treatment during transportation are the initial sources of artefacts.

Since it is possible to go down a long path of implementing an image analysis regime without being able to assess the quality of the information gained, a simplistic approach has been adopted to each step, similar to the approach of McBratney and Moran (1990). The methodology adopted in this experiment has used a similar system where a white pigmented resin is applied *in situ*, the samples removed, cut and polished and the cut soil section examined by image analysis methods. From initial experiments, to screen samples and detect any differences between treatments, it was clear (Figure 6.1) that such differences did exist; subsequent analysis was tailored to do no more than quantify this for selected samples.

Figure 6.1 Soil sections from plots 348 and 372

Sample section from plot 348 - control plot (no trees)

Sample section from plot 372 - *Acacia nilotica* planted 1988

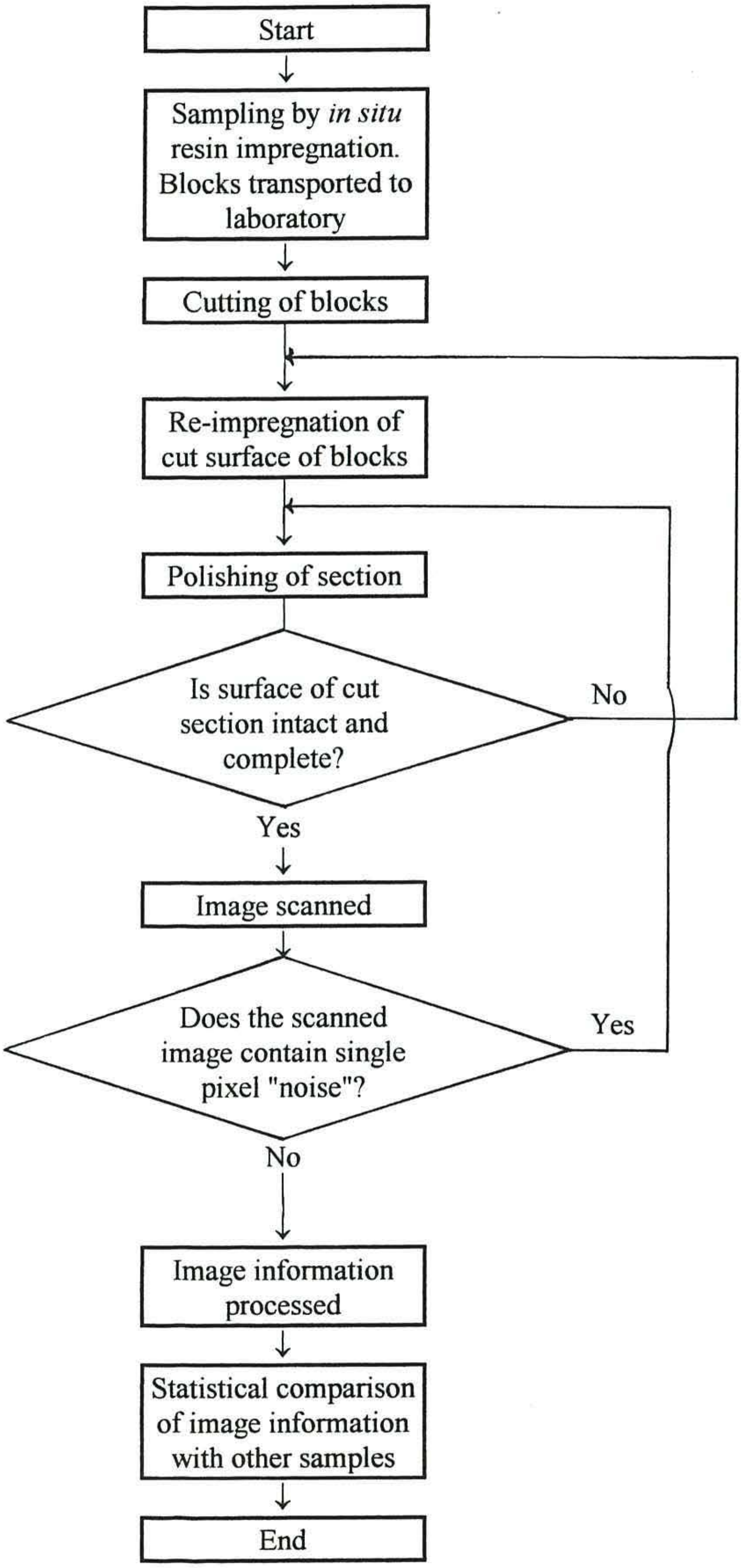


6.3 IMAGE ANALYSIS METHODS EMPLOYED

6.3.1 Introduction

The image analysis has been performed in a series of steps, each of which a balance has been sought with the steps preceding and following, in terms of the precision and accuracy attained. Thus no one step has been identified and singled out as introducing artefacts, all must be considered to have done so. The steps undertaken in this experimentation from the collection of samples, obtaining images through to image processing are shown as a flow chart in figure 6.2.

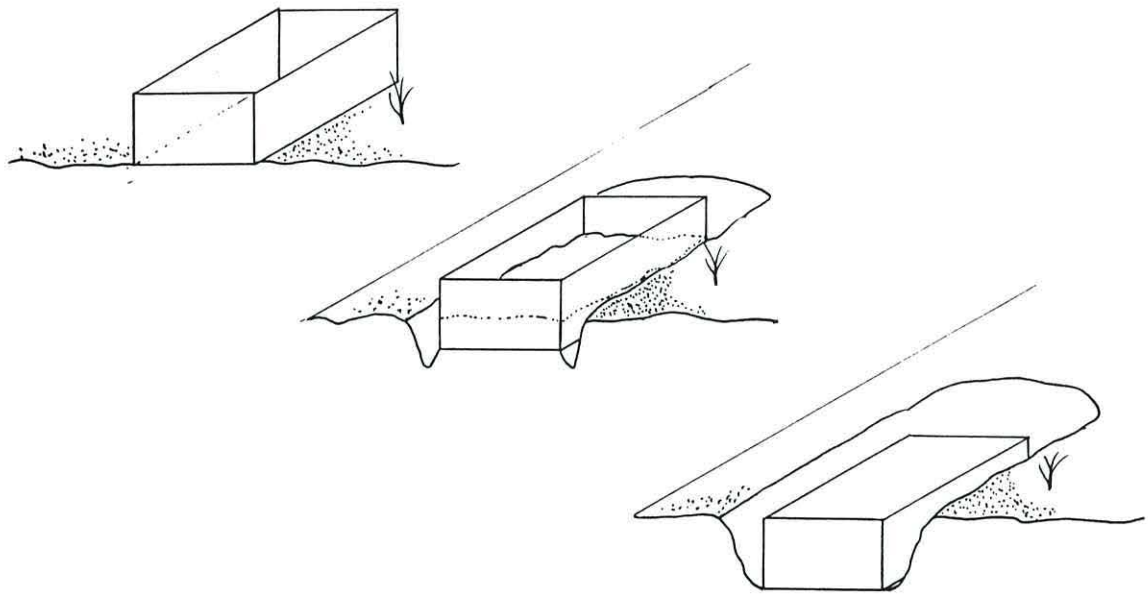
Figure 6.2 Flow Chart of processes used in the image analysis of meso-structure samples



6.3.2 Method: Impregnation of soil blocks *in situ*

Open ended (top and bottom) metal boxes (300 mm x 125 mm x 90 mm) were coated with a layer of releasing wax (Simoniz "Original Fine") and inserted into the dry soil with the minimum of surface disturbance. This process was achieved by partially excavating with a knife around the metal box being inserted (Figure 6.3). The possible collapse and loss of soil structures through slaking and infilling precluded moistening the soil to insert these metal formers.

Figure 6.3 Insertion of a metal former for collecting samples



The resin applied was required to be: as fluid as possible, in order to mimic water entry into the soil; quick setting, in order to be of practical use in the field; and capable of being used and stored at the high working temperatures (35-40°C) encountered in the field. This latter consideration precludes the use of crystic (polystyrene) resin systems which polymerise in this temperature range during prolonged storage. Resin systems which can meet these criteria are based on epoxy resins which set quickly, are readily handled, can be diluted with Butanone (Acetone) to adjust the setting time and can survive high temperature storage conditions.

The resin system adopted is that of Dexter, (1991). This is Ciba-Geigy Araldite MY 753, Hardener HY 951 and a white pigmenting agent Araldite DW0131. These were mixed in the ratio 100:15:1 w/w respectively. The manufacturer's recommended mixture (100:10:1) uses less hardener, however it was found necessary to increase the amount, presumably due the interference of the particular soil-matrix in the polymerization process. In the high temperature working conditions found in Nigeria, this mixture was found to require dilution with acetone (11% v/total w) in order to increase the setting time. The resin system has been demonstrated to polymerize succesfully at a range of moisture contents (Dexter, 1991), in this case the moisture content of the surface soils was minimal (<3 %).

The resin was applied to the soil in one batch by means of a specially constructed metal funnel, the amount applied being calculated using an assumed porosity of the soil block of 50% and an assumed density of the resin mixture of 1 g cm^{-3}.

For instance:	
size of block:	300 x 125 x 90 = 3,375,000 mm^3 = 3,375 cm^3 ≈ 3,400 cm^3
if 50 % available for impregnation, then amount of resin required:	3,400 ÷ 2 = 1,700 cm^{-3}
if density of resin mixture assumed to be 1 g cm^{-3} then:	1,700 g required of resin mixture
The quantities used, per block, were:	1,500 g resin 225 g hardener 15 g white pigment 200 cm-3 acetone

After the resin had set fully (*ca.* 30-40 minutes) and the heat generated by the epoxy reaction had dissipated (*ca.* 2-3 hours), the block was removed from its position in the field by carefully adzing beneath it (see plate 6.1). The sample was then covered with foil and sealed airtight to prevent moisture entry during transportation back to the laboratory in the UK.

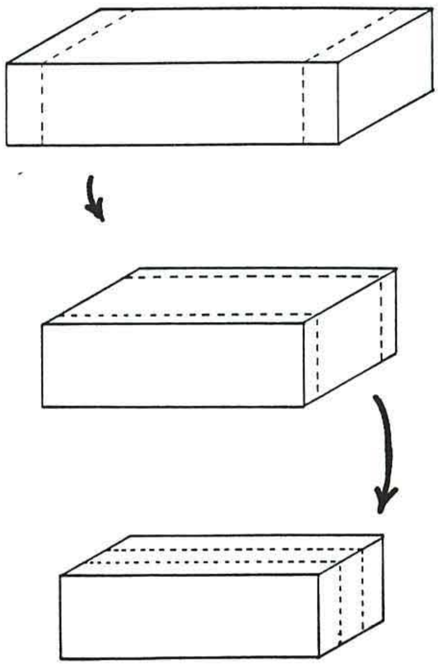
Plate 6.1 Casting soil samples *in situ*

Plate 6.2 Removing soil samples cast *in situ*

6.3.3 Method: Cutting and polishing

A trial sample block (10 cm x 8 cm x 5 cm) taken from sandy soil was cut open using a mechanical reciprocating hacksaw in Nigeria. The appearance of this block indicated that the resin had not penetrated completely into the soil block, particularly where a massive soil-matrix structure was encountered. There was however sufficient cohesion to allow the main blocks to be succesfully cut without the use of cooling liquid in order to prevent such liquids damaging the samples. To achieve this, a circular tungsten carbide tipped masonry saw (30 cm ∅, 0.6 cm cut-width) was used to cut the blocks. The cutting diagram is shown in figure 6.4.

Figure 6.4 Cutting Diagram of soil blocks



The surfaces of the cut sections were re-impregnated using small quantities (5 cm^3) of Araldite. The mixture used was Resin: Hardener: Pigment 100:15:1 w/w with no addition of acetone. This was applied with a spatula and allowed to set. The block was then dry sanded on a mechanical belt-sanding machine with 60 grit (*i.e.* 240 µm) paper. The resulting surface was then polished by hand on a glass plate using 53 µm silicon carbide grinding powder and Abralap 2A cutting oil. This last step took between 15 minutes and 2 hours for each surface. The samples were then cleaned with petroleum ether and inspected for flaws in the surface (*e.g.* resin falling out of shallow pores). If necessary, the surface was impregnated again and the steps outlined above repeated (*cf.* flow-chart, figure 6.2).

6.3.4 Method: Image analysis

Image analysis was undertaken on the cut and polished sections of the impregnated blocks. For use with the Delta-T Scan software, a direct scan of the soil block section, rather than a video image, was taken using a Hewlett Packard "Scanjet-plus" flat-bed scanner. This operated at 300 d.p.i. resolution *i.e.* having a nominal pixel size of 7.2 x 10^{-9} m^2 (7.2 x 10^3 μm^2). The dedicated Hewlett Packard acquisition software was set to produce a 1:1 image, *i.e.* no scaling of the physical size, and at a threshold contrast was easily set visually to maximise the amount of information whilst keeping the amount of single pixel "noise" to a minimum. This was also helped by using a glass plate on the scanner bed and microscope immersion oil (BDH - Tropical grade) between this plate and the soil block surface. Whilst this qualitative method of thresholding may be criticised for being simplistic, it has the merit of obtaining a balance between the amount of information required and the intrusion of extraneous artefacts. Such a view is supported by Glasbey & Horgan (1994) in their discussion of thresholding methods. It was found that sandy textured samples with a slightly rough surface occasionally produced poorer images. This was assumed to be due to the lifting on the surface of individual (sand) grains when the block was cleaned with petroleum ether. In these instances the block was re-polished (*cf.* flow-chart, figure 6.2) and the scanning repeated.

The scanned image was stored as a TIFF version 5.0 type file (TIFF, 1988). This file type contains information on the scanner and acquisition software settings, such as the resolution of the scanner. These files were then imported to the image analysis software, "Delta-T Scan" (Delta-T, 1993), which was selected in order to quantify the number and size distribution of the pores found in each sample section. Alternative software (*e.g.* GIS such as GRASS and ARC/INFO) were considered but rejected either on the grounds of expense or unnecessary complexity. Besides its relative simplicity, the other advantage of the Delta-T software is its use of scanned image files rather than frame-grabbed images obtained from video-cameras.

The method employed by the Delta-T scan software is to analyse each discriminate object. In this instance it was found to be easier to distinguish a pore space than a complete soil aggregate since the aggregates may be touching one another and not recognised by the software as separate entities. This same problem also precludes the calculation of the channel sizes of soil pores by Markov chain analysis (Dexter, 1991), since what the observer would visually extrapolate to be a contiguous vertical pore may not be complete in the cut section analysed. Since the main objective of this experiment is to ascertain if there are any distinguishable differences due to the influence of the field treatment (planting of *A. nilotica* trees), then such steps appear to be unnecessary.

The Delta-T Scan software uses the methods and algorithms described below for the calculation of variates. These are of two types, one relating to the overall image of the soil section (% area covered by pores), the other six (height, width, area, perimeter, shape and number of included objects) relating to identified pores within each image.

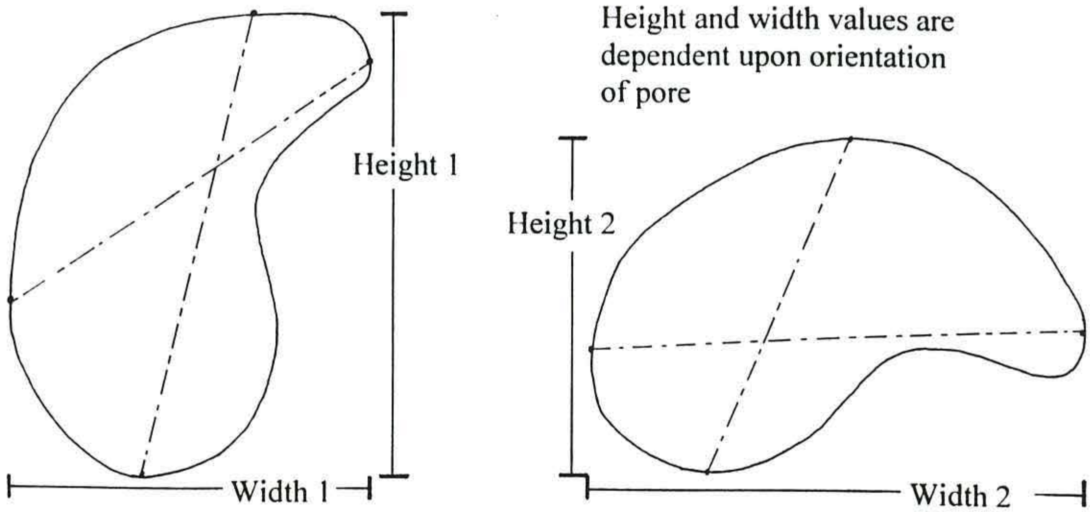
Percentage area covered by pores

The area of the overall image covered by the pores is calculated from the total number of pixels that are "on" (black *vs.* white) *i.e.* they are part of an object, as a percentage of the total image area when expressed in terms of the number of pixels.

Pore Identification

Apart from the total area covered by pores, all other variates rely on a discrete pore being identified before the parameters of the pore are measured. There needs to be at least two pixels joined edgeways together in the image for the software to recognise this as a pore and perform its analysis. The height (h) and width (w) of each pore are calculated using a "fitted box" method. The values that these take is dependent upon the orientation of the image (Figure 6.5).

Figure 6.5 Box fitting method of finding pore height (h) and width (w) (after Delta - T, 1993)



The values used in the quantification of each object in the image are:

Pore Area : A_{total}

The area of each pore is calculated from the number of pixels, scaled to real size, thus:

$$A_{total} = K\frac{N_0}{(N_0 + N_1)}$$

where

$N_0 = Number\ of\ pixels\ "on"$

$N_1 = Number\ of\ pixels\ "off"$

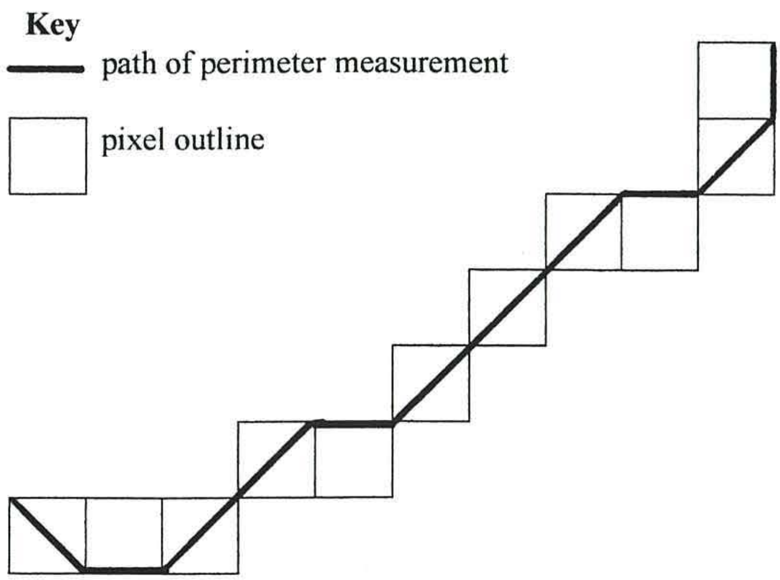
$K = image\ area\ scale\ factor\ (to\ convert\ to\ mm^2)$

$A_{total} = area\ of\ pore\ in\ image\ (mm^2)$

Perimeter : $\mathbf{P_m}$

Measurements of the perimeter of each pore are obtained by tracing a line through the outermost pixels forming the pore image. For each pixel this line is taken either along one edge of the pixel or diagonally between opposite corners. The line is not drawn diagonally through two pixels which adjoin edge to edge. Figure 6.6 shows all the possible pixel combinations and the manner in which these are measured.

Figure 6.6 Perimeter tracing



Pore shape: $S = \frac{P_m}{P_e}$

The pore shape is derived from a ratio of the measured perimeter P_m and a perimeter

$$P_e = 2\pi\sqrt{\frac{1}{2}\left[[d_s/2]^2 + [d_l/2]^2\right]}$$

calculated assuming that the object is an ellipse where d_l = largest diameter of enclosing ellipse and d_s = smallest diameter of enclosing ellipse.

Number of included objects in each pore: **I**

If the pixels counted and measured for an object are considered to be "on" it is possible to calculate the number of smaller objects included within the object by simple summation. Included objects must have at least 2 pixels joined edgeways that are not recognised as part of the larger pore object, *i.e.* they are the "off" pixels. This value is of interest in this instance because of the infilling of larger pores (*e.g.* cracks due to shrinkage, root channels and faunal burrows) by material translocated by either physical or biological processes.

The TIFF image files for each of the soil sections are presented in Appendix 6. This appendix also contains the data generated by Delta-T scan software for each section, where the above variates are calculated for each pore.

6.4 INTERPRETATION OF IMAGE ANALYSIS RESULTS

6.4.1 Introduction

As has been shown in figure 6.1 there are differences clearly visible between images which can be discriminated subjectively. Therefore the challenge of the opto-mechanical image analysis described in section 6.3.4, and for techniques used in the interpretation of this information, is to be able to recognise these differences and assign values scaled to an appropriate experimental level. In this instance, this is at the plot level. The mean values calculated at this plot level can then be compared statistically to test for the effects of the imposed experimental treatments - a comparison between plots with and without trees. The latter two stages are described in this section. Three different methods (see sections 6.4.2, 6.4.3 and 6.4.4) have been used to analyse the images. The methods used, their reproducibility and the implications of the results obtained are discussed in section 6.5.

6.4.2 Image analysis data interpretation:
Method 1 - Statistical analysis of parameters measured on each object

The parameters measured for each object or group of objects can be compared individually after being summarised at the plot level by collapsing the data from lower experimental levels. The parameters that were measured for each object (pore area, pore perimeter, pore shape and number of included objects in pore) and the percentage area of the image covered by pores have been analysed between the experimental treatments as described below:

The ***percentage area of the images covered by pores*** for each site plot were compared between the tree treatments in a mixed, random and fixed, analysis model. The results are plotted as a bar chart in figure 6.7, showing an increasing trend in pore area from the northern sand-rich plots (338, 362) to the southern clay-rich plots (348, 372). The statistical comparison of these results shown in table 6.1, does not account for the spatial position of the plots.

Figure 6.7 Mean percentage area covered by pores in analysed images of soil sections and mean percentage sand content of plots analysed.

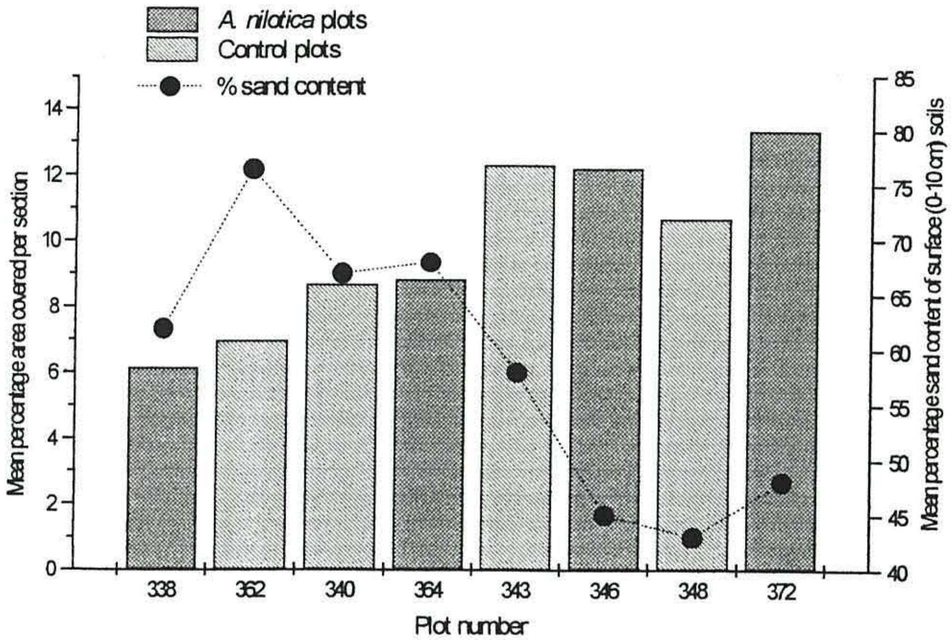


Table 6.1 Comparison of the percentage area of each image covered by pores

Variate	Plots with trees (n=4)	Control plots (n=4)	SED	P<0.05
1. Mean percentage area covered by pores	10.31	9.43	1.94	ns

For the data relating to the individual objects, these were first ranked and selected according to ***perimeter***. This allows for the greatest coverage of the pore system in terms of length. The largest 100 pores were selected, thereby eliminating pores less than the order of 5 x 5 pixels (1.8 x 10^5 μm^2). The ranked values of these variates are shown in figures 6.8 - 6.11. The data for each image for each variate were then used for analysis at the site plot level of the 4 - 13 separate images per plot, using a "mixed analysis model" *i.e.* with both fixed and random effects to compare the effect of the tree treatment. These results are shown in table 6.2.

Table 6.2 Comparison of plot treatments using mean values of 100 objects from each image

Variate	Plots with trees n=4	Control plots n=4	SED	P<0.05
2. Mean pore area	0.110	0.056	0.027	*
3. Mean perimeter	1.070	0.60	0.213	*
4. Mean pore shape	85.70	65.96	8.450	*
5. Mean number of included objects	0.001	0.000	0.000	ns

As can be seen from figures 6.8.-6.15 these data have a lot of perturbation where very large and very small pores are seen. Therefore the statistical analyses have been repeated using a data subset where both the information from very small and the very large pores has been removed. It is an obvious criticism that such selection of a range of information for comparison reduces some of the randomness in the data analysis model. Therefore particular attention has been paid to the criteria adopted in the selection of the threshold limits of the data window used. The lower limit of including only the 100 largest pores has been adopted so removing any object that may be considered as "noise". The threshold for the smallest pores was selected to eliminate pores smaller than 5*5 pixels, thereby any single pixel noise in the image will affect each object by no more than 4% of its total area. Whilst the removal from the data analysed of objects which may be noise in the image is easily accounted for and justified, the setting of a threshold for larger objects is more difficult to achieve objectively. The method chosen is to remove the 10 largest pore objects since they are so large they are likely to be occurring with a periodicity on the field site that cannot be accounted for using this sampling method (>0.5 m) and can be considered macro-scale features. These data subsets have been analysed in the same manner as before, using a mixed fixed and random effects model, the results being shown in table 6.3.

Table 6.3 Comparison of plot treatments using mean values of 90 pore objects from each image

Variate	Plots with trees (n=4)	Control plots	SED	P<0.05
2. Mean pore area	0.112	0.057	0.027	*
3. Mean perimeter	1.090	0.611	0.216	*
4. Mean pore shape	86.47	66.66	8.464	*
5. Mean number of included objects	0.001	0.000	0.000	ns

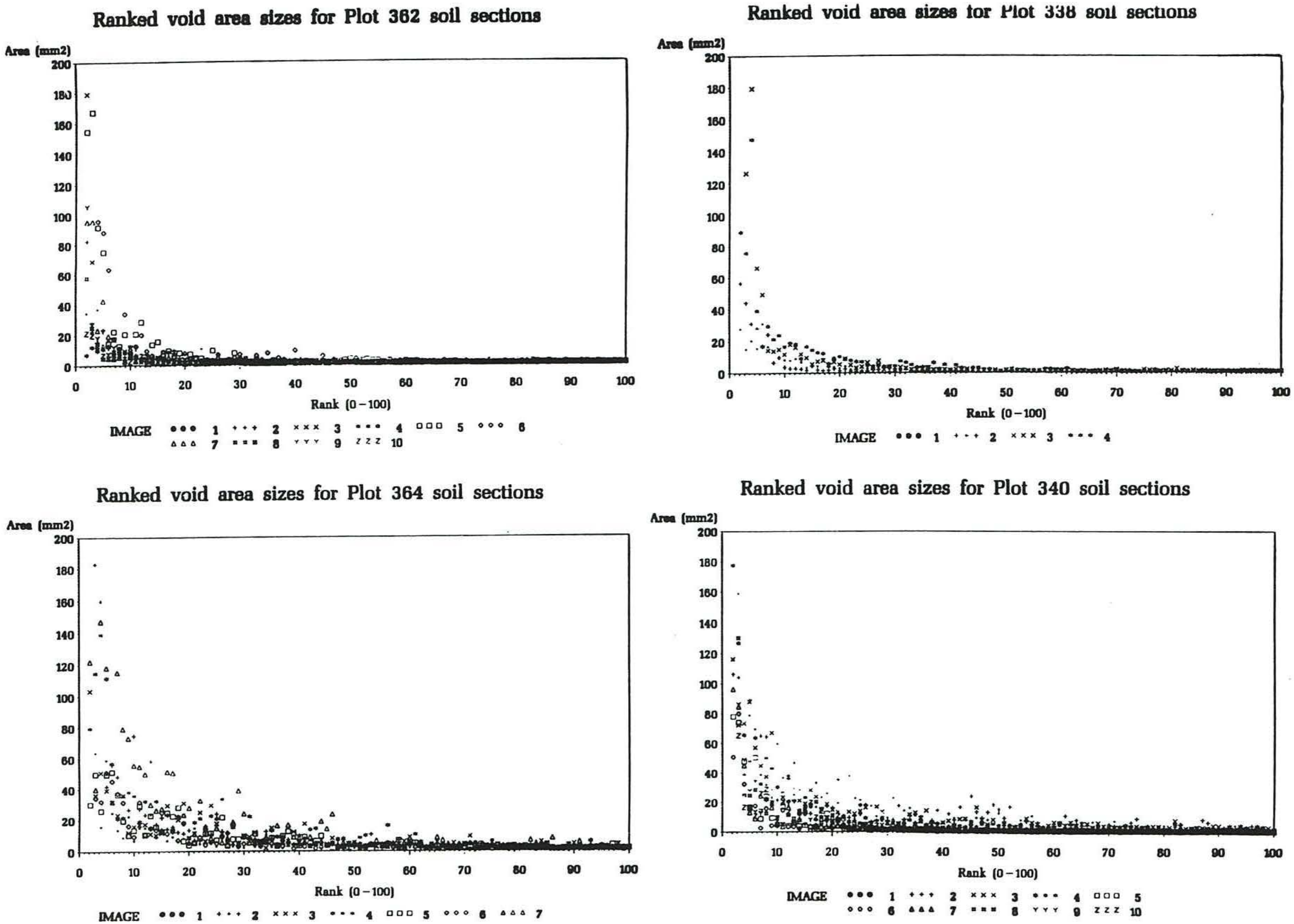


Figure 6.8 Pore area - ranking of largest 100 objects scanned

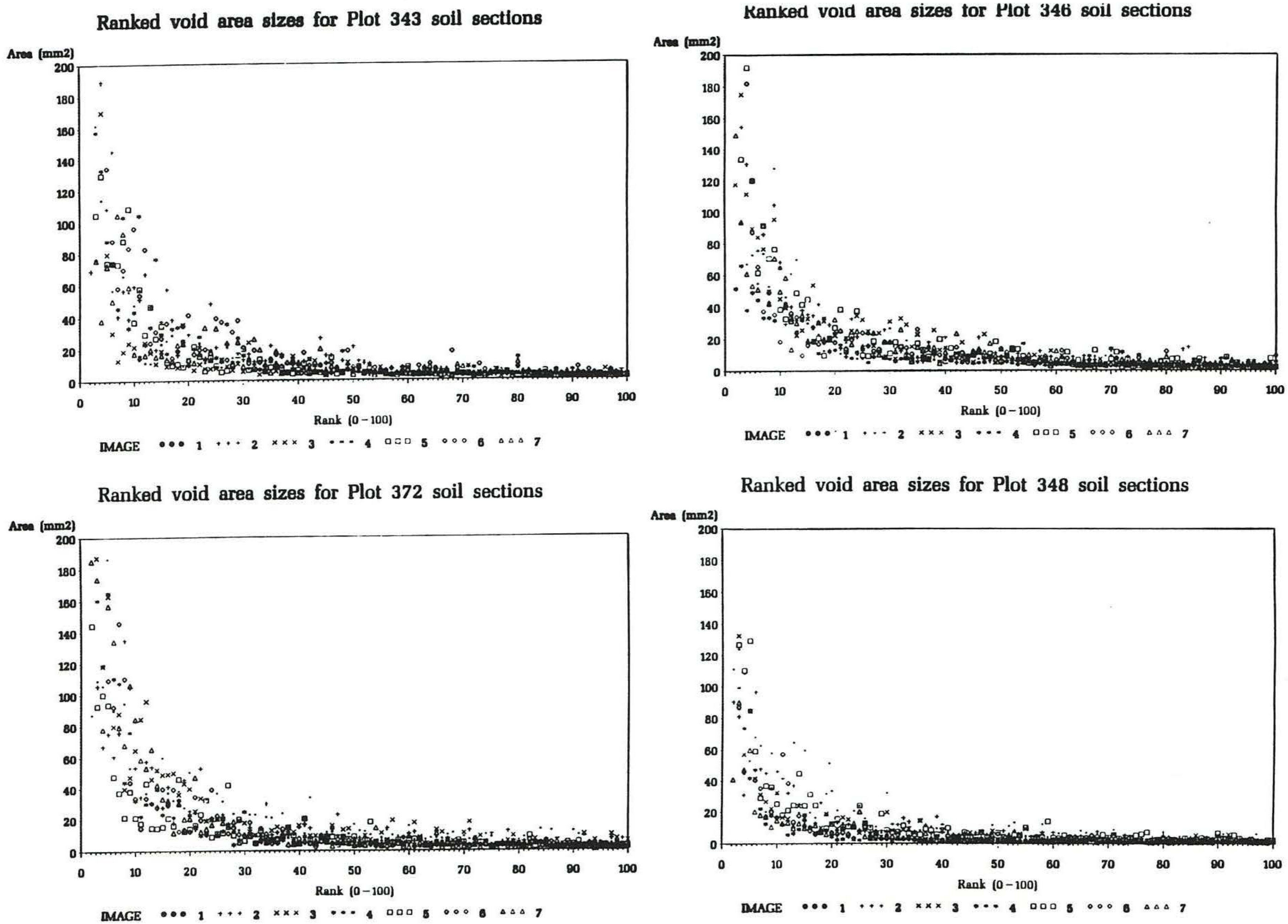


Figure 6.8 cont'd. Pore area - ranking of largest 100 objects scanned

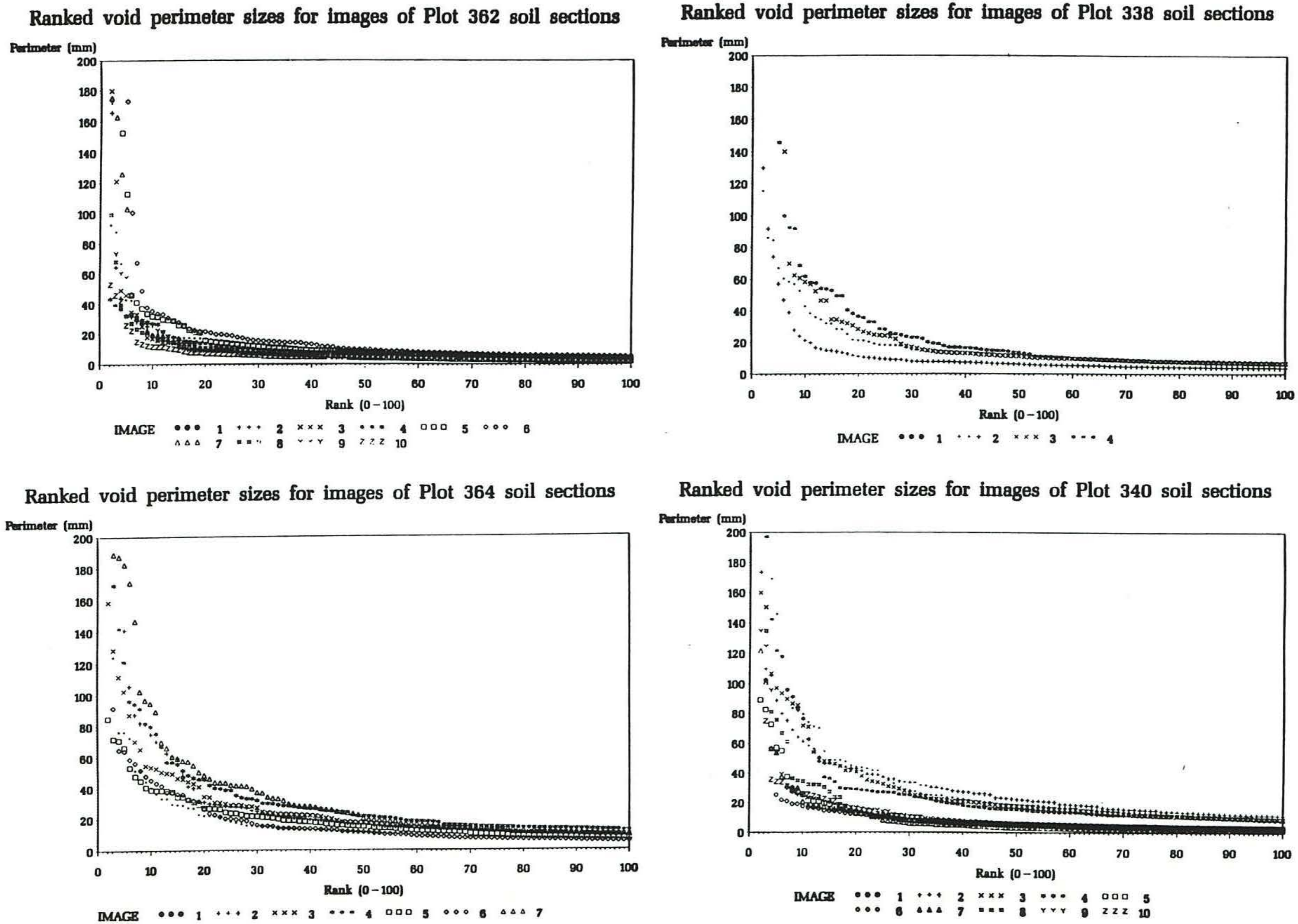
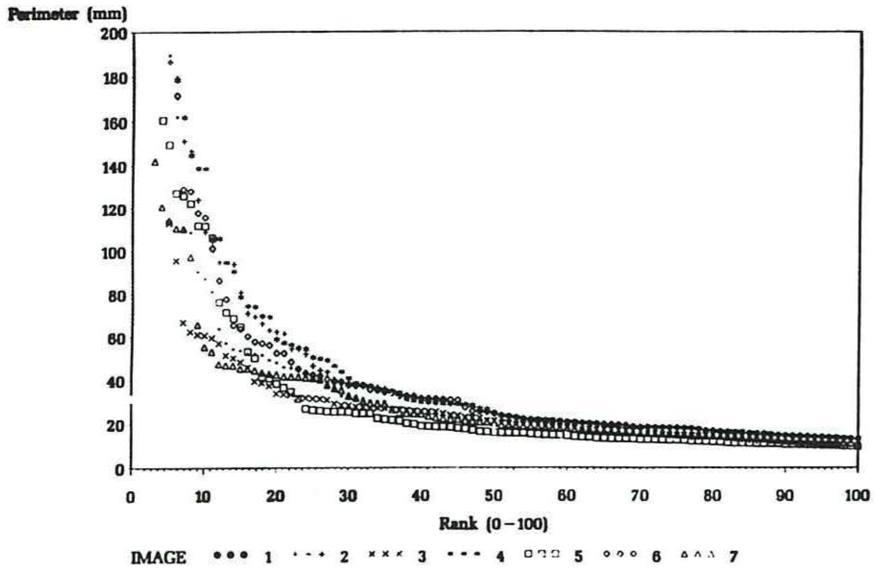
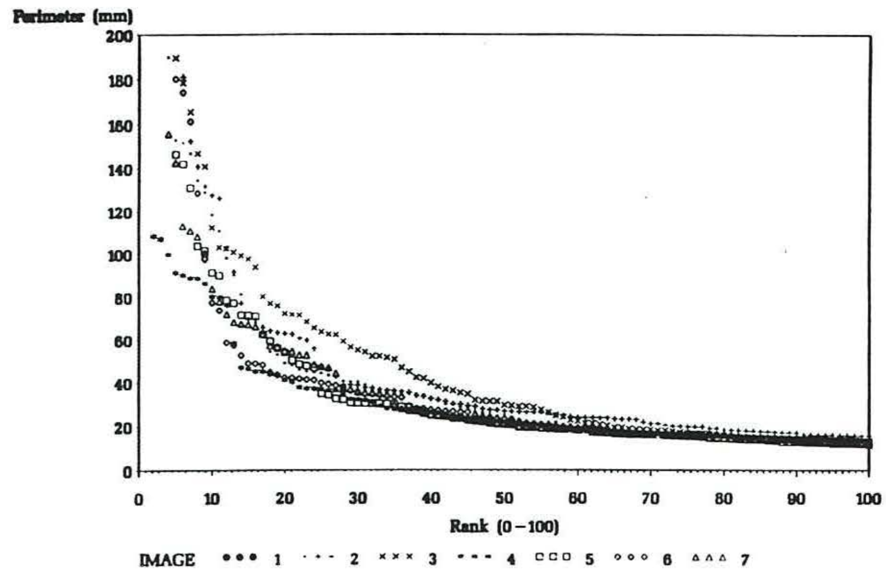


Figure 6.9 Pore perimeter - ranking of largest 100 objects scanned

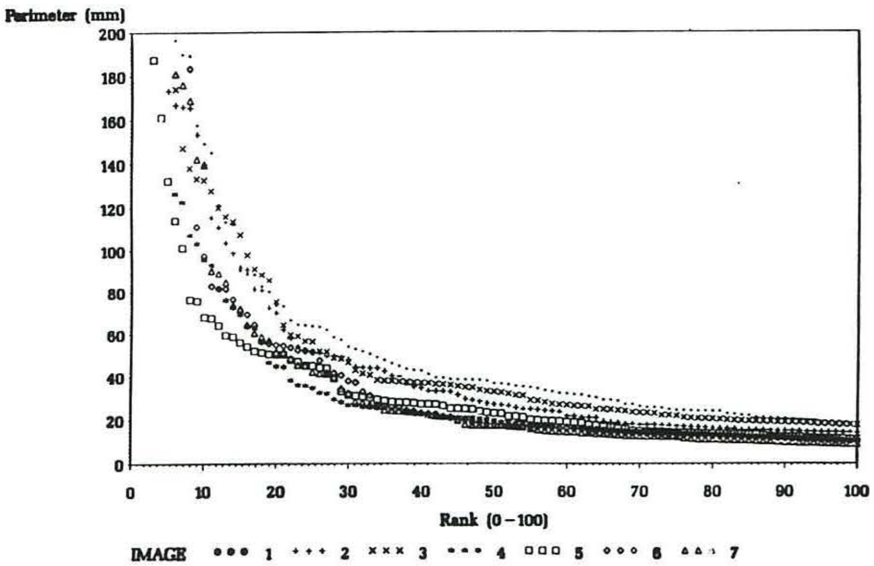
Ranked void perimeter sizes for images of Plot 343 soil sections



Ranked void perimeter sizes for images of Plot 346 soil sections



Ranked void perimeter sizes for images of Plot 372 soil sections



Ranked void perimeter sizes for images of Plot 348 soil sections

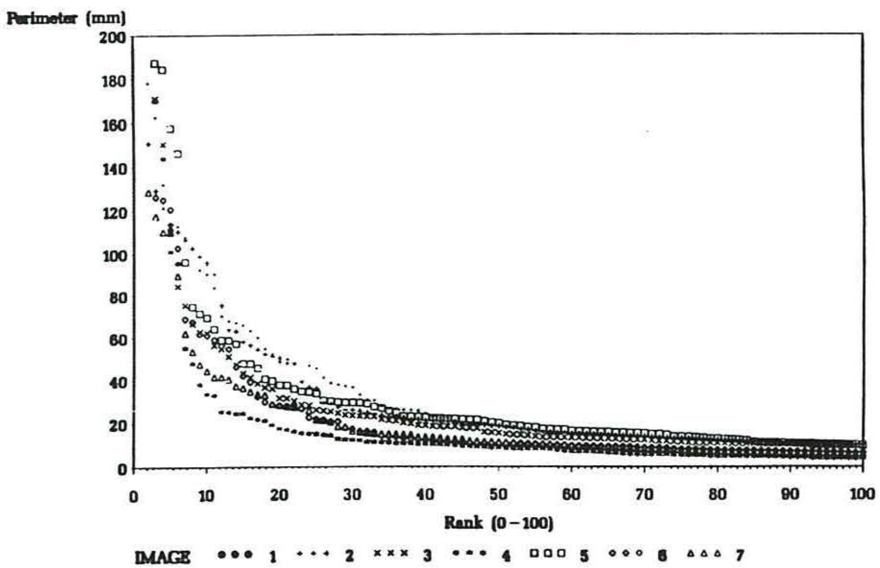


Figure 6.9 cont'd. Pore perimeter - ranking of largest 100 objects scanned

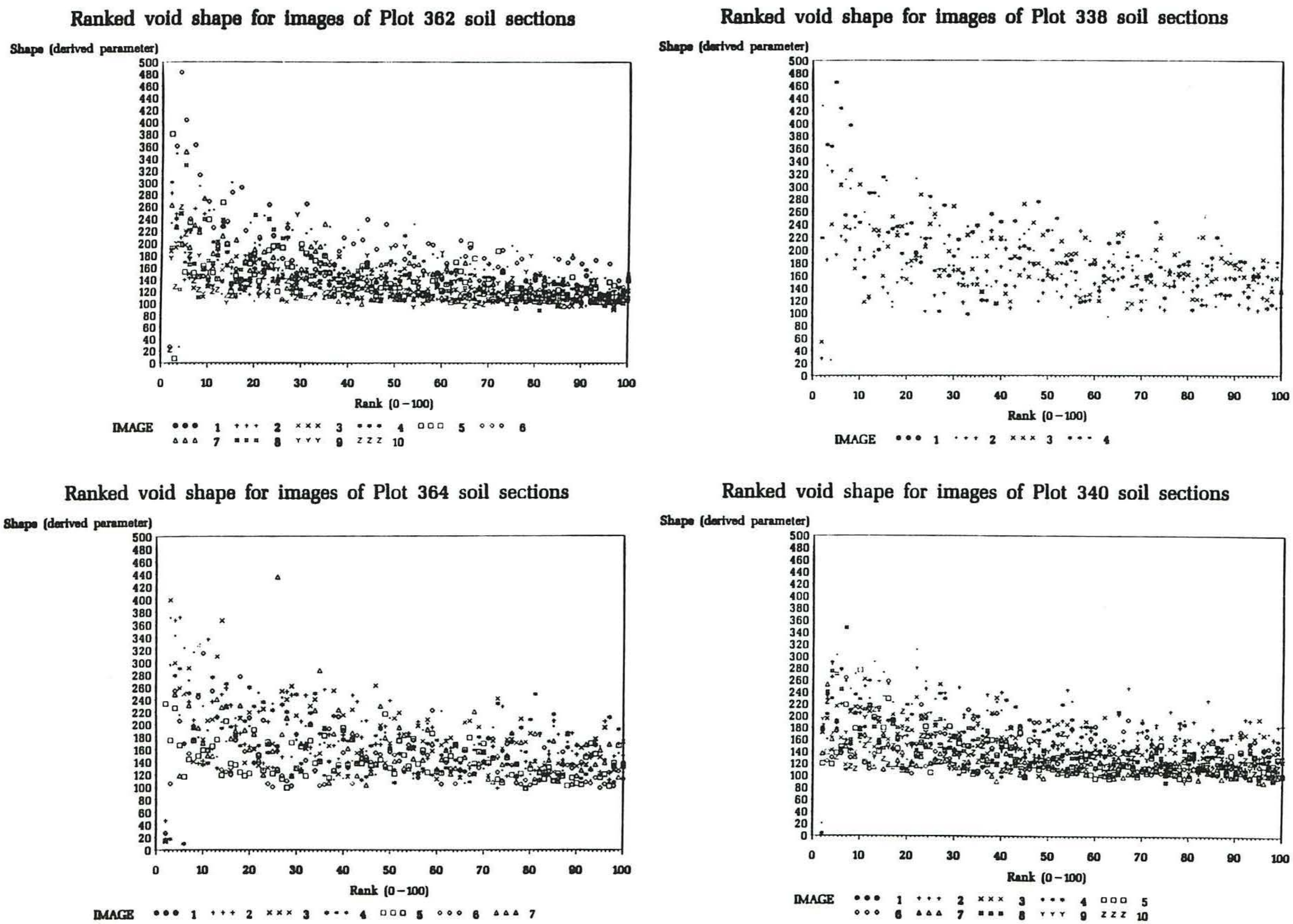
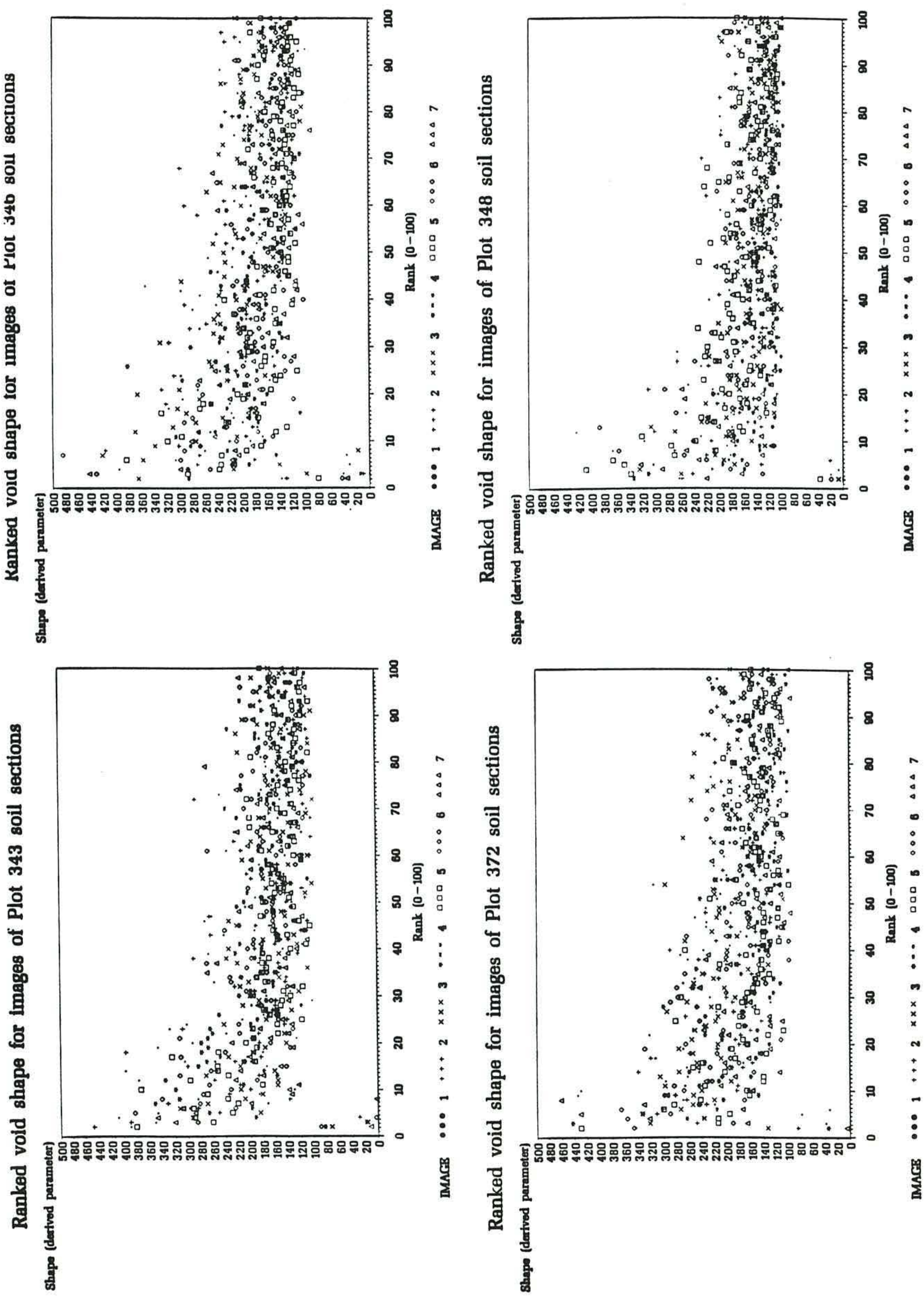


Figure 6.10 Pore shape - ranking of largest 100 objects scanned

Figure 6.10 cont'd. Pore Shape - ranking of largest 100 objects scanned



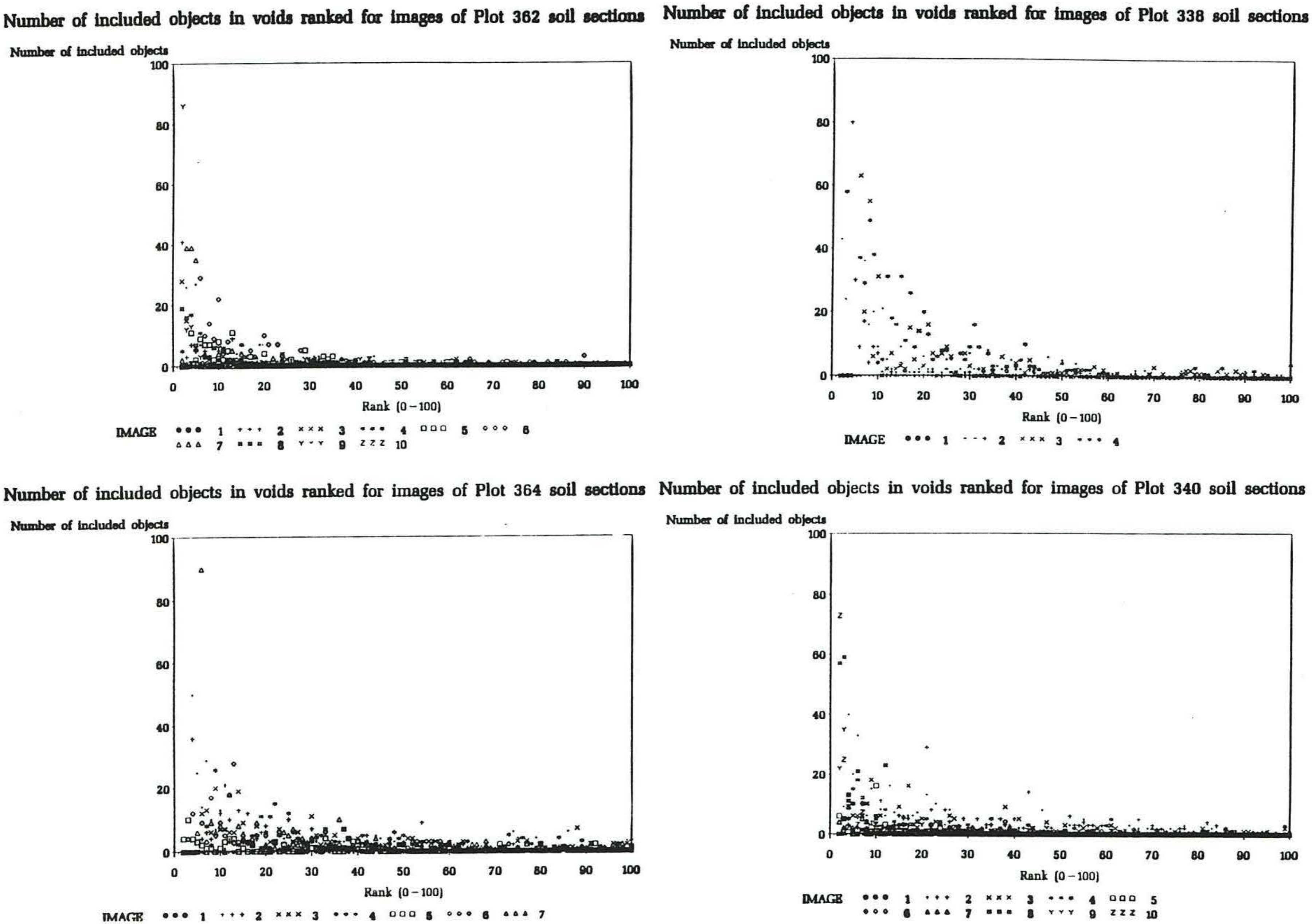


Figure 6.11 Number of included objects - ranking of largest 100 objects scanned

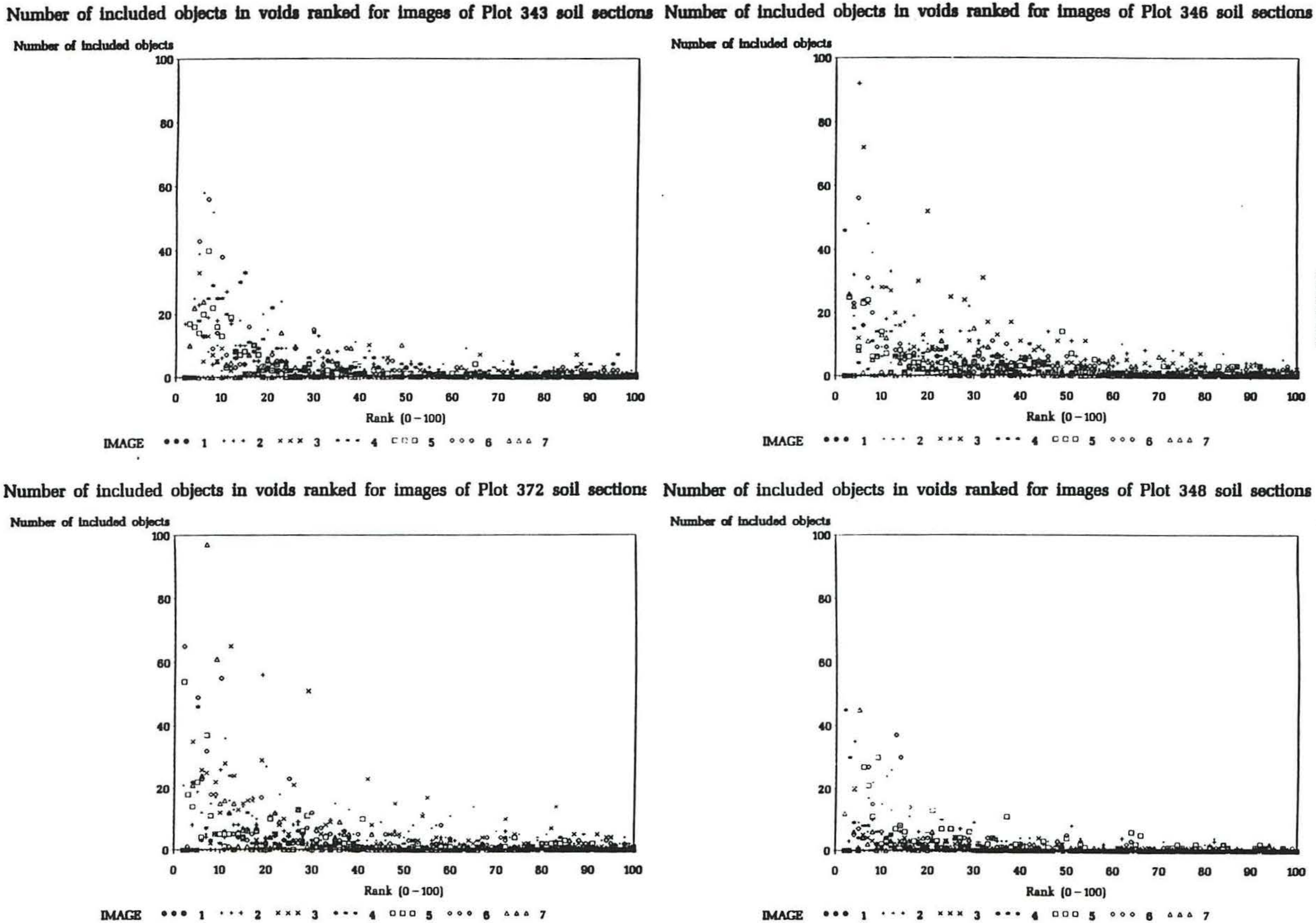


Figure 6.11 cont'd. Number of included objects - ranking of largest 100 objects scanned

6.4.3 Image analysis data interpretation:
Method 2 - Using fractal dimensions as a summary variate

The image analysis of each section of each soil block yields a varying number of defined pore objects. The five parameters measured (section 6.3.4) provide for a range of comparisons between them according to the experimental design. However, it is useful to try and derive a summary variate that can be used at the individual soil section level, which may also then be used to assess the reproducibility of the methodology. Ideally, such a value should have a simple nominal value and be comparable to those from other locations.

One such method, utilising fractal geometry, has been derived and used in a small number of applied studies on soils (*e.g.* Crawford, *et al.*, 1993). The method involves calculating the "fractal dimension" of the soil pores in a particular soil block, this value of fractal dimension can then be used as a summary variate to compare different locations. This method has been found useful in the characterization of soil pores in terms of their suitability as habitats for soil meso-fauna (Kampichler & Hauser, 1993).

The use of "fractal dimensions", first elucidated by Mandelbrot (1977), to relate to natural forms has been discussed in mathematical terms by many authors (*e.g.* Barnsley, 1993). Crawford *et al.*, (1993), in their description of the application of fractals to describe soil aggregates, derived several fractal terms, including fractal dimension. The following derivation of the fractal dimension is adapted from Kampichler and Hauser (1993) and uses the data available from the image analysis (section 6.3.4).

The intersection of a three dimensional block of soil with a plane produces an image where three-dimensional soil pores appear as two-dimensional areas. Mandelbrot, (1977) identified a simple relationship (equation 6.1) between the fractional dimension of the perimeter of the sectioned pore, *Dp* and the pore surface dimension *Ds* (*e.g.* Ringrose-Voase, 1987) of the same pore.

Equation 6.1

$$Dp = Ds - 1$$

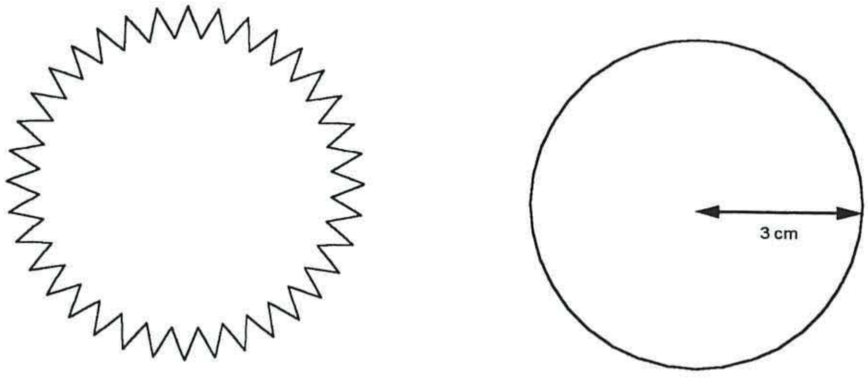
A further development of such fractal studies is to use the relationship of area A and perimeter P, in normally dimensioned (*i.e.* non-fractional) space, to quantify the contortion of the perimeter of the pore. This is given (Mandelbrot, 1987) as:

Equation 6.2

$$P \approx A^{Dp/2}$$

In this instance a completely smooth pore surface will have $Dp = 1$, ($P \approx A^{1/2}$) whereas for a very contorted figure $Dp \approx 2$, ($P \approx A$). This is illustrated in figure 6.12. In order to obtain the dimension Dp from equation 6.2, a plot of ln (A) *vs.* ln (P) will have a regression line of slope $Dp/2$. Therefore this can be solved for Dp, and from equation 6.1, Ds obtained. This single value of Ds can be used for comparison with other soils provided that the same methods and criteria for respectively measuring and selecting soil pores have been used.

Figure 6.12 Example relationships between area and perimeter



Area: 9π cm^2
Perimeter: 15.5π cm

Area: 9π cm^2
Perimeter: 6π cm

To obtain the fractal dimension Ds for the images of the soil sections, a graph of ln (P) *vs.* ln (A) was plotted for each image (figure 6.13). A principal component regression analysis was used to find the slope of "best-fit line" for these data. The principal component regression is used since this method avoids making a distinction between the two variates (area and perimeter), in terms of their dependency upon one another. The slope of the fitted regression line alone gives some measure of the tortuosity vs. extensiveness of the pores in the soil. Also plotted in each graph of figure 6.13, is the function P = A; this function represents lines or objects changing length whilst remaining the same thickness. The results of the statistical comparison between the two tree treatments is shown in table 6.4.

Table 6.4 Comparison of the fractal dimension between treatments

Variate	Plots with tress n=4	Control plots n=4	SED	P<0.05
Fractal dimension *Ds*	2.34	2.40	0.04	ns

Figure 6.13 Plot of ln(perimeter) *vs.* ln(area) of scanned objects

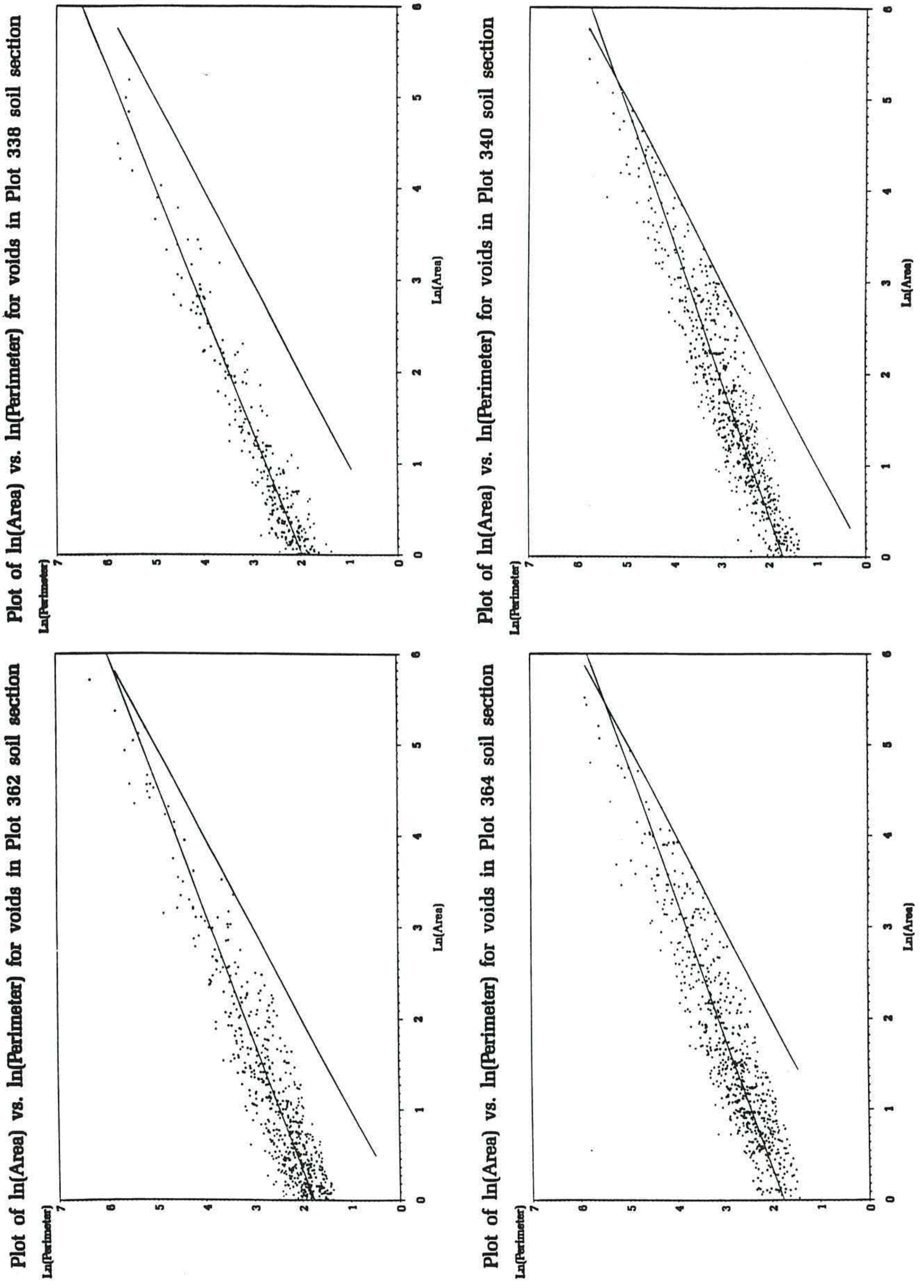
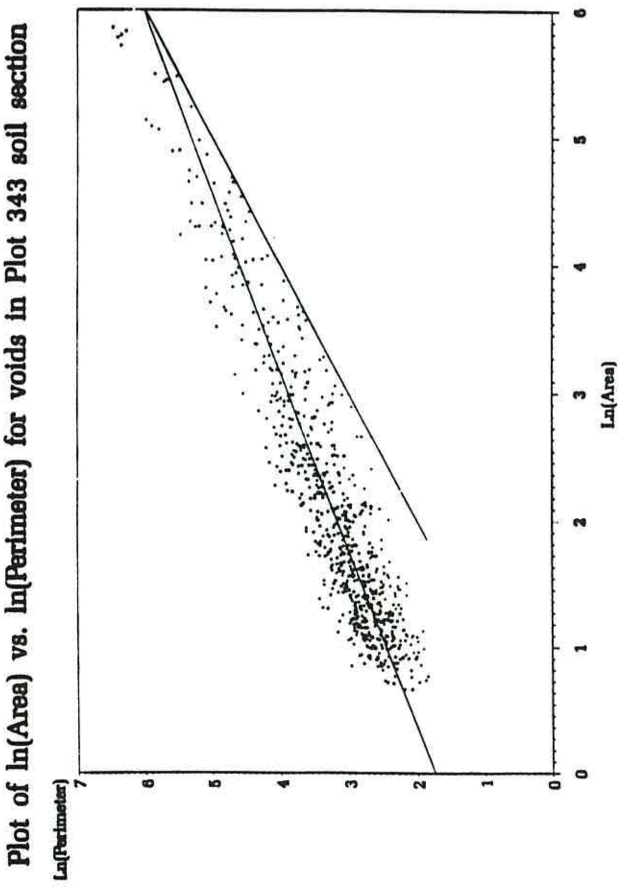
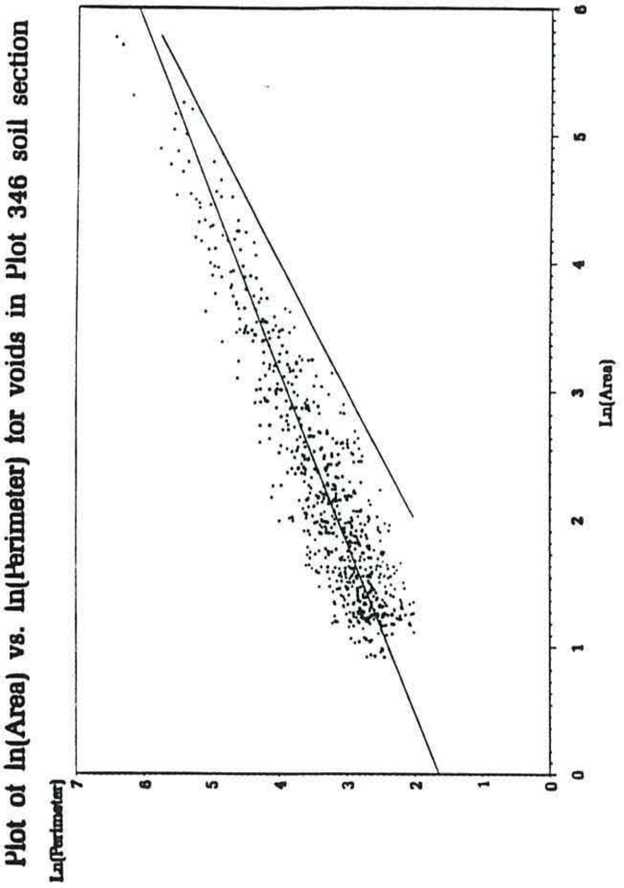
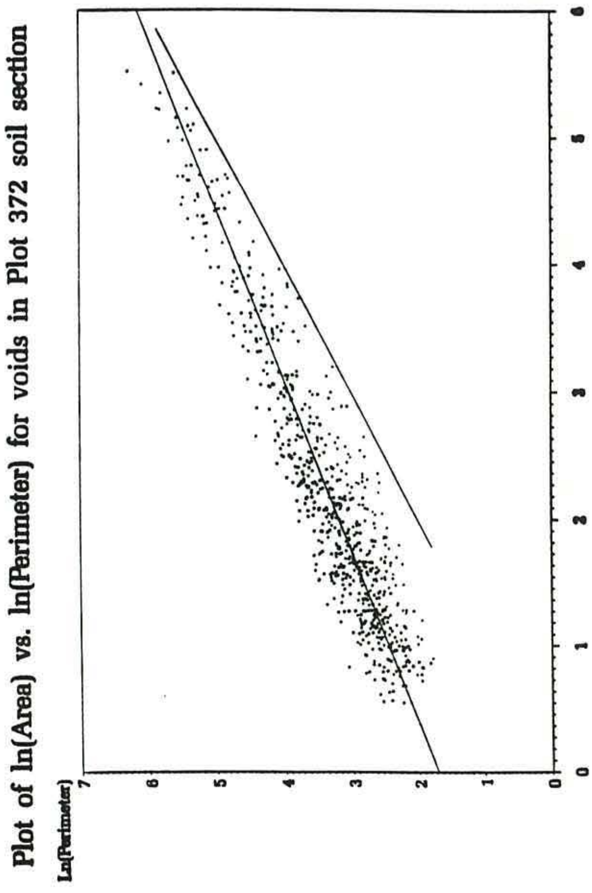
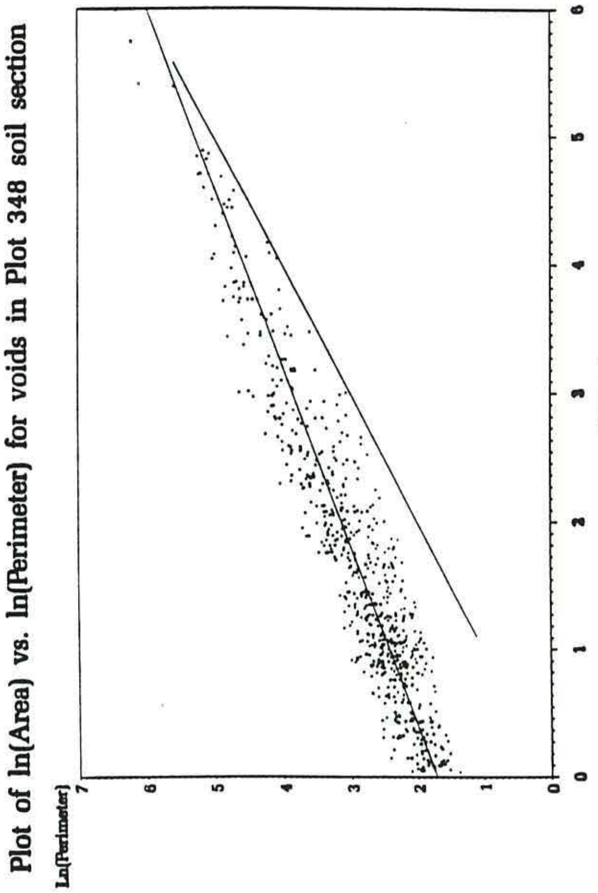


Figure 6.13 cont'd. Plot of ln(perimeter) *vs.* ln(area) of scanned objects









6.4.4 Image analysis data interpretation: Method three - subjectively categorised ranking of soil structure images

6.4.4.1 Introduction

When the soil sections used for the image analysis are first viewed there are clear differences between them (*e.g.* figure 6.1). These differences have been categorised and analysed using the image analysis techniques described in sections 6.2.2 through 6.4.2 As such, the image analysis techniques have tried to formalise the relationships between the structural image parameters. The visual inspection of the image of each soil section provides an alternative method for ranking the differences between images. This approach has been investigated in order to try and ascertain whether soil structure descriptions made by the human eye match those found by image analysis methods and vice versa.

6.4.4.2 Methods employed

Subjective ranking is frequently used in situations where human preferences are of central concern (*e.g.* wine tasting). When such measurements relate to physical objects, they use human perception as an integrating device, making a judgement on each image and placing them relative to other images. In this instance, this technique may show differences that are too difficult to describe objectively using opto-mechanical image analysis and statistical interpretation procedures.

A brief experiment has been conducted, in order to test the hypothesis that ranking by humans matches the ranking of the images by "mean percentage area covered by pores" from the Delta-T Scan software (see Method 1; section 6.4.2). Sixty images of the soil sections were selected. In order to rank these images, a set of seven individuals who have no knowledge of the rationale of the experiment and no knowledge of the treatments imposed, were informed of the orientation of the images and their method of production, and that pores were toned black. With this brief amount of information they were asked to rank the images from "most structured" to "least structured". With the people used in the study, there is no introduction of expert knowledge, *i.e.* the individuals are naïve toward soil nomenclature and description. In this manner, the ranking is ascertained by a "heuristic" rather than a scientistic, formalized process.

6.4.4.3 Results

The ranked scores from the participants were compared with the results from the image analyses by the Delta-T Scan software. This was undertaken using cross correlation analysis performed using Base SAS and SAS/Stat software (SAS, 1991). The half correlation matrix between the respective rankings is shown in table 6.5.

Table 6.5 Half correlation matrix of the observers rankings (A-G) and the ranking by percentage total area covered from the Delta-T scan software.

Observer	A	B	C	D	E	F	G
B	▲						
C	ns	ns					
D	ns	▲▲	ns				
E	▲▲	ns	▲	▲▲			
F	▲	ns	ns	ns	ns		
G	ns	ns	ns	ns	ns	ns	
Delta-T	ns	▲	ns	ns	ns	ns	ns

▲▲	highly correlated (+ve)	$r > 0.40$
▼▼	highly correlated (-ve)	$r < -0.40$
▲	significantly correlated (+ve)	$0.40 > r > 0.25$
▼	significantly correlated (-ve)	$-0.40 < r < -0.25$
ns	not significant $p > 0.05$, $n=61$	$-0.25 < r < 0.25$

This matrix shows few significant correlations, suggesting that this ranking technique could be more usefully applied only with relatively small numbers (*i.e.* < 20) of images. Also, these results show no consistent trend amongst the observers' rankings, although all of the significant correlations are positively correlated; this must be due to some agreement between the rankings. Despite these few significant correlations, it must also be concluded that there is no significantly correlated common viewpoint amongst the observers when compared with the results of the Delta-T Scan software for only the ranking of observer B was significantly correlated with these results. This implies that either the observers were creating their ranking on different criteria, *e.g.* only ranking using the largest objects, or that there are too many images to rank successfully. This latter point would again suggest that the technique may be successfully developed only for use with smaller numbers of images.

6.5 SUMMARY OF IMAGE ANALYSIS RESULTS

The image analysis and description of soil sections using Delta-T scan software successfully distinguished between different pore systems which are visually apparent when several sections are compared (*cf.* figure 6.1; all sections shown in appendix 5). The statistical comparison of the data for individual parameters of the objects classified as pores has shown significant ($P<0.05$) differences between plots with trees and control plots for three of the measured parameters: area, perimeter and shape. These three parameters are indicative of the observed increase in smaller aggregates on some of the more clay-rich soils. It was also expected that the number of included objects in the pores would have also acted as a good indicator of the state of this pore network. However the nature of these data is that many (>40%) have zero value, thereby upsetting the analysis. The selection of the objects by perimeter rather than by area compounds this factor. The obvious alternative of selecting by pore area, would not cover as much of the pore system and was therefore rejected as a method to use.

Whilst the information gained from the individual object variates has shown significant differences due to treatment, both summary variates (fractal geometry and total area covered) have not shown significant differences. All of the data presented have revealed a trend toward greater pore area and greater pore sizes in the plots with the trees. This suggests that there is a tree effect in the development of greater pore sectional area and, presumably, greater pore volume in the soil of these plots.

The analysis of the fractal dimension summary variate shows a trend towards larger, longer and less tortuous pores in the plots with trees. This may be an indicator of either aggregate breakdown *i.e.* a large complex of less stable aggregates or conversely the development of a larger pore network with aggregate stability improved or unaltered. The percentage area covered by pores also indicated that there is a larger network of pores in the plots with trees. Nevertheless the graph showing this variate (Figure 6.7) does reveal a striking trend from low values of the sandy surface plots to higher values of the clay-rich plots. These samples were, however, taken in the dry season after the clay rich soils have re-developed their polygonally cracked structures.

Despite the inclusion of some very large objects, the mean values of pore area and pore perimeter calculated for each image used in the analysis were low compared to the size of these large objects, emphasizing that the analyses are dominated by the smaller objects. This is most readily seen in the distribution of the data in the logarithmic graphs of object areas *vs.* perimeters for each image (figure 6.13). In these graphs there is a dominance of small objects with only a few larger objects. These graphs, used to obtain the mean fractal dimension of the pores, all indicate that the larger values start to follow the perimeter = area relationship where length is changing but the thickness (breadth) is invariant. This suggests that these large objects are long and thin and that they cannot get any thinner without becoming two objects. This would appear to correspond to the planar cracking that develops in these soils, particularly those that are clay-rich.

The method of ranking images visually as a method of separating sections from "most" to "least" structured, was not successful. There was some commonality between the observers but few significant correlations between both the observers and the ranking generated from the Delta-T results. It is possible that the method could be applied, but only on relatively small batches of images. As such, the method could possibly be more useful in identifying particular features in the soil sections (*e.g.* root channels) than in assessing an "amount" of structure development.

The overall conclusion is that there is a significant difference in the pores, between plots with trees and control plots. This is likely to be reflected in the aggregate size distribution which can be expected to show a reduction in aggregate sizes in the tree plots. Although there is no significant difference in the summary variates examined, these both followed the same trend, indicating a larger network of pores in the tree plots. This would suggest that these larger pore systems are the product of tree influences and, if stable, would allow greater water infiltration. Aggregate stability is the subject of the following section and water infiltration is discussed in the following chapter.

6.6 AGGREGATE STABILITY

6.6.1 Introduction

In the field experiment at New Marte the central element of the overall hypothesis has been the influence of tree biomass inputs upon the soil structure and the consequent effects upon the infiltration of water into the soil. The subsequent uptake and use of the water reaching the soil has, in turn, been the major interest in the parallel studies on plant physiology. In order to test the main hypothesis, the preceeding soil structural studies have been undertaken examining the distribution and shape of pores. These studies do not, however, describe the strength of the soil aggregates. Therefore, since the breakdown of soil aggregates may act as an impediment to the infiltration of water, the stability of the soil aggregates under the environmental stresses found at New Marte is of specific interest.

Measurement of the aggregate stability of a soil at a particular instant, (a "snapshot") will not, however, portray a soil's true structural characteristics since these will vary temporally depending upon the most recent activities or conditions on or within the soil. Soil aggregates will themselves be in a long-term cycle of repeated formation degradation and destruction (Oades and Waters, 1991). In the circumstances of this field experiment, the aggregate stability of the soil is of specific importance when the soil is subjected to the first rainfall events of the year, before the inundation of the whole area. Therefore the experimental procedure adopted has attempted to mimic these conditions found in the field in order for the knowledge gained to be transferable.

6.6.2 Methodology

The methodology adopted follows that for the chronosequence profiles (see sections 3.5.1-3.5.4) and has used the same equipment (Plate 6.3).

6.6.3 Sampling

To test the effect of the trees on the soil aggregate stability, samples were taken from the plots used for the other soil structural experimentation at New Marte, *i.e.* 1988 year of planting in Block 4 (figure 5.1). Samples were collected from 10 random positions within each plot. All samples were collected from a depth of 0-10 cm in the

1993/4 dry season period, since this avoided problems due to artificial drying had the samples been collected when wet. The 10 samples were then bulked together to form a representative sample from each plot or position. This is a total of 160 discrete data measured in 80 separate independent experiments.

6.6.4 Method

For each measurement a 100.00 g sub-sample of the 2 mm - 5.6 mm size-fraction was used for each of five (0.5, 1.0, 2.5, 5.0 and 10.0 minutes) different time periods of sieving. The sieve sizes used (1400 μm and 500 μm) were the same as those used in the experimentation on the regional chronosequence samples as described in section 3.5.4. Plate 6.4 shows the two sieve mesh-sizes with, as an example of the result of each experiment, the material retained on these sieves from a clay-rich sample.

Plate 6.3 Wet-sieving apparatus

Plate 6.4 Soil aggregates retained after a wet-sieving experiment
Left: 1400 μm mesh sieve; Right: 500 μm mesh sieve

6.6.5 Results of sieving experiments

Each individual sieving experiment produces two data: dry weight of aggregates for the two sieve mesh-sizes. These data have been combined with those from the other measurements made for each plot to produce a "decay curve" of aggregate stability. These data are expressed as a series of graphs in figure 6.14. These graphs are plotted with each data represented by a symbol. The lines drawn through these symbols connect the simple mean values of each pair of experiments. The lines are plotted to give some indication, by eye, as to the temporal trend of each set of measurements. This method of presenting aggregate stability results is consistent with the style adopted by several other authors (*e.g.* Kandeler and Murer, 1993; North, 1976).

In addition to this graphical treatment the results have been analysed statistically to make treatment (tree plot *vs.* control plot) comparisons. A series of covariates have been considered in these analyses.

6.6.6 Other results used as covariates in statistical analysis

Apart from the results of the individual wet-sieving experiments, a series of other factors were considered as co-variates in the statistical analysis of the experiments. Of these a soil textural component was considered most appropriate. Soil texture, expressed as percentages of sand, silt, clay and fine clay has been measured and reported previously (section 4.3). For the eight plots used in these wet-sieving experiments, the results are shown in table 6.6.

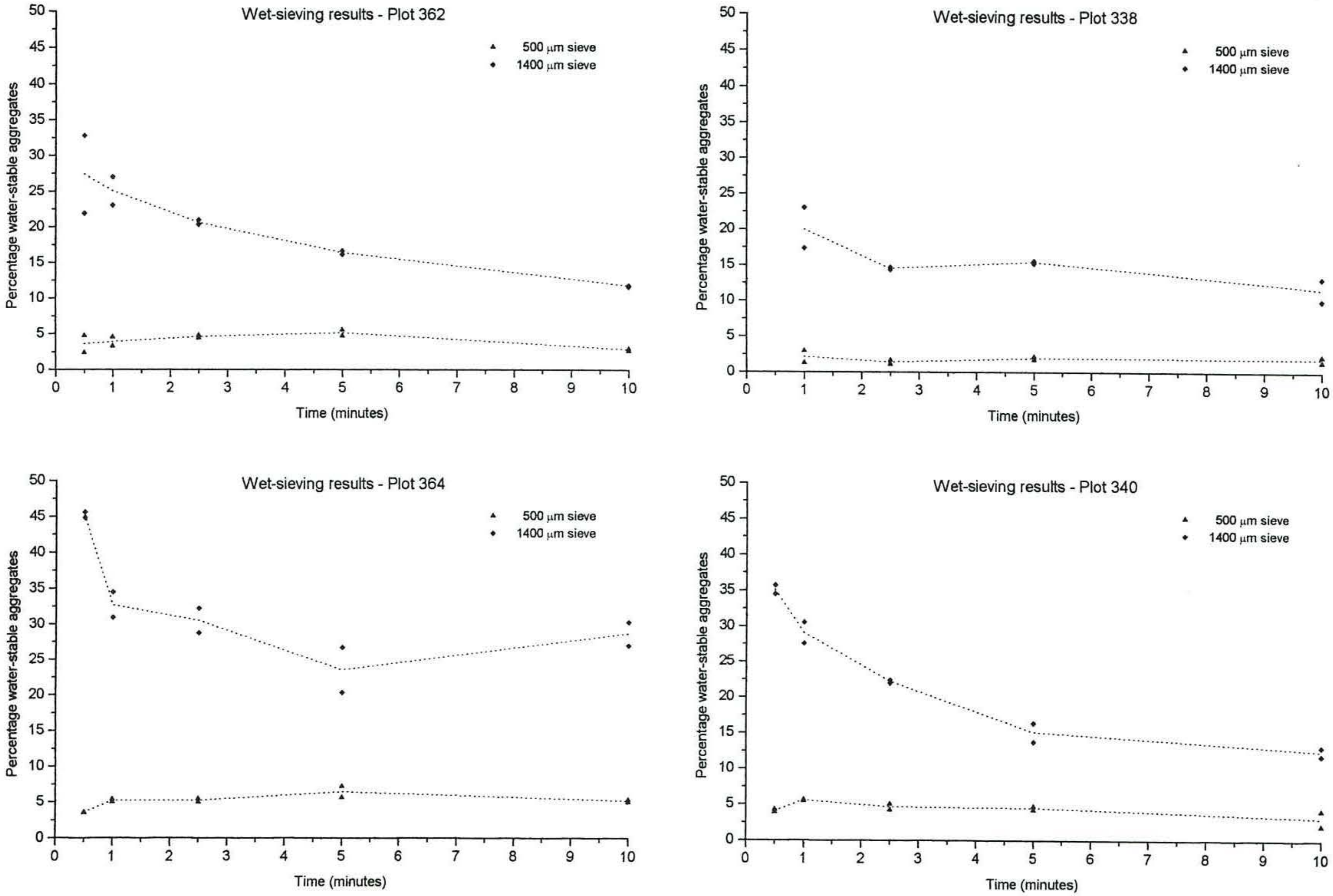


Figure 6.14 Aggregate stability measurements

Figure 6.14 cont'd. Aggregate stability measurements

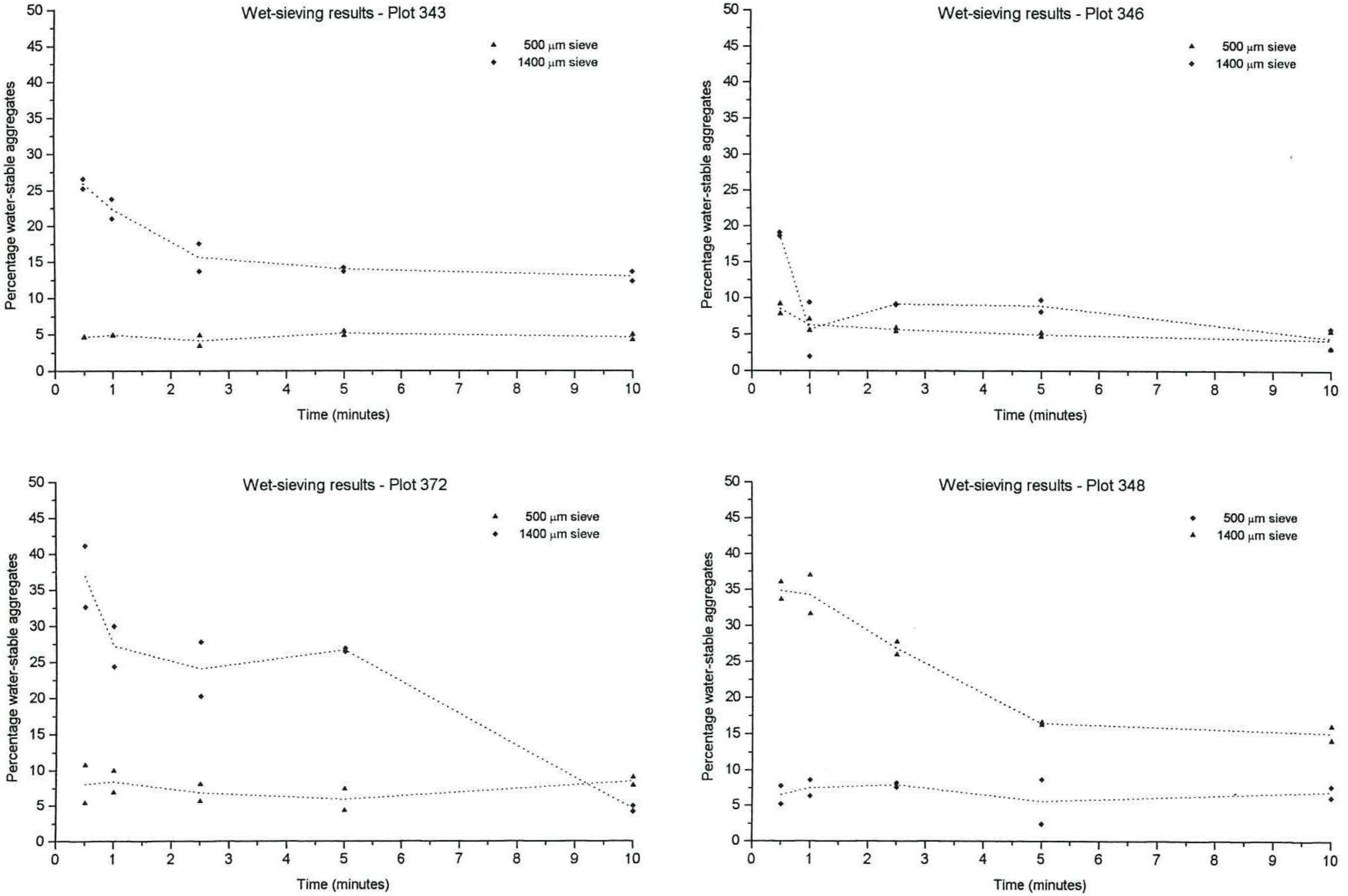


Table 6.6 Soil textural information
(Expressed as weight percentage N.B. fine clay is a subset of the clay component)

Plot	Sand (2000-63μm)	Silt (63-2 μm)	Clay (<2 μm)	Fine clay (<0.2 μm)
338	62.0	17.1	20.9	4.4
340	67.0	12.9	20.1	7.6
343	58.7	21.5	19.9	2.5
346	45.8	15.7	38.5	13.0
348	43.8	21.4	34.8	16.3
362	76.5	18.1	5.4	0.0
364	68.0	-	-	-
372	48.4	20.7	31.0	14.5

6.6.7 Statistical analysis

All of the time periods were compared between the two treatments for both the upper 1400 mesh sieve and for the lower sieve. It was expected that any differences would be most evident at either the short time periods or at the longest time period of ten minutes. For the former case the greatest influence on the aggregates stability will be the explosive effect of the release of trapped air from within the aggregate. For the longer time period the effect of slaking on the aggregates will be the dominant factor on their disintegration.

As indicated in table 6.7, no significant differences are evident due to the effect of trees at any of the time periods used in the aggregate stability measuremnts. To consider the effect of the soil texture the analysis was repeated using the weight percentage sand (Table 6.6) as a fixed effect in the analysis model *i.e.* as a covariate. This analysis again revealed no significant differences between the tree and no tree treatments, but the fixed effect of the sand content was significant ($P.<0.05$).

Table 6.7 Results of statistical comparison of plot treatments

Sieve Size	Time (minutes)	Mean value Tree Plots (g)	Mean value Control plots (g)	SED	P.<0.05
1400 μm sieve	0.5	34.01	30.52	8.29	ns
	1.0	21.43	27.71	7.02	ns
	2.5	19.39	21.37	5.76	ns
	5.0	15.15	15.32	3.15	ns
	10.0	12.50	12.85	5.88	ns
500 μm sieve	0.5	6.11	5.09	0.96	ns
	1.0	5.36	5.58	0.67	ns
	2.5	4.62	5.42	0.85	ns
	5.0	4.71	5.10	0.96	ns
	10.0	4.76	4.48	0.89	ns

6.6.8 Discussion of aggregate stability results

Since the methodology is empirically derived, it is subject to the introduction of artefacts due to the particular methods adopted. There have been several reports of changes in the wet aggregate stability when the soil has been subjected to air-drying or oven-drying prior to the sieving analysis. This has been reported as both increasing (Churchman & Tate, 1987) and diminishing (Munroe & Kladivko, 1987) aggregate stability. In this experiment, all the samples were collected in a uniform air-dry state so that this factor will have been minimised and is therefore discounted.

Each data presented in the graphs of figure 6.14 is representative of an individual experiment. Each of these experiments uses a different soil sub-sample from the same bulk soil sample for the plot concerned. Examining the results in figure 6.14 shows that, with one exception, each pair of experiments has produced similar results despite the inherent variability of the sub-samples. This shows that the methodology is robust, reproducible and has "good" precision.

The lack of any significant difference between the plots with trees and those without, might be explained in terms of several factors. Firstly any differences arising are expected to become more prominent over longer time periods, since the process of aggregate formation is a slow process. The trees on the plots were in their sixth year of growth when these measurements were made, a longer period of say ten or twenty years may be required before larger scale effects attributable to the presence of trees are detected by this method. However, the methodology would appear to have good precision and such measurements could usefully be made after such time periods.

Secondly, the effect of the varying soil texture will mask any changes occurring due to trees. The most prominent differences in figure 6.14 are the low initial values, indicating a rapid destruction of aggregates, for plots 362 and 338, the most sand-rich of the plots, when compared with the textural measurements of all of the other plots (Table 6.6). This emphasizes the effect of soil texture on these measurements. There is unfortunately not enough replication within the experimental plot structure to allow comparison between the treatments after separating the plots into two sandy and clay classes.

Various authors have written on the relationship between the stability of soil aggregates and the quantity and nature of the soil organic material, usually with the latter expressed as loss-on-ignition. Haynes and Swift (1990) have reported that unstable aggregates (breakdown after less than 1 minute of wet sieving) have lower organic contents than stable aggregates (not broken down after 15 minutes wet sieving). Similar results have been arrived at on a variety of African soils (Monnier, 1965), and conclusions drawn recommending the implementation of fallow rotation cropping on certain field sites.

6.7 Soil Structure - summary and conclusions

The underlying objective of the experimentation undertaken has been to assess the differences in the soil structure, if any, occurring as a result of tree inputs to the soil, by comparing measurements from plots with trees with those from control plots without trees. The experimental techniques used have been selected and developed to be robust and readily repeatable. Also, the methods developed, particularly aggregate stability measurements were demonstrably reproducible implying good precision, such that any longer term (10-15 year) changes could be compared, repeating the techniques described.

The significant differences in the pore area, pore perimeter and pore shape parameters found in the images of the soil sections would indicate an effect due to the presence of trees. The trend indicated by these results and those of the fractal summary variates of these analyses is one of increasing pore area in the sections taken from positions in tree plots. This is coupled with a reduction in the size of the soil aggregates. If the greater volume of the pore network is to be beneficial in the context of the agroforestry system described, then the stability of the aggregates is particularly important. That there is no significant difference in aggregate stability between the tree plots and control plots suggests that the aggregates in the tree plots are as stable as those in the control plots and, conversely, as prone to slaking and structural collapse. The aggregate stability measurements are prone to operator and procedural differences, and it must be recognised that the aggregate samples tested were collected in a dry state to minimise this problem. However, the use of dried aggregates has been reported (Williams *et al.* 1966) as increasing the differentiation in the results obtained between treatments involving inputs of organic materials. Haynes and Swift, (1990) made use of this phenomenon to improve their methodology, but in the experimentation at New Marte this process did not increase the separation of results between treatments to produce significant differences in their analysis.

The collapse of the soil structure would impede the infiltration of water into the soil, suggesting that a longer time-period may be required if the aggregates are to be stabilised by physico-chemical factors, particularly organic material inputs. That there are identifiable differences in the pore networks but not in the aggregate stability measurements further suggests that the trees are either directly influencing the physical disturbance of soil aggregates by, for example, root action; or are indirectly influencing this by altering other biotic factors such as the population of soil meso-fauna; or a combination of both of these processes. Oades (1993) emphasises the rôle of biotic factors in aggregate formation and destruction, particularly the effect that increased biotic activity has on retaining structure regardless of whether a physical or biological process, or both, were involved in the forming of the soil structure.

In the New South Wales region of Australia where a variety of vertisolic soils are found, significant changes in the surface structure have been reported at scales of <100 m (Little *et al.* 1992). As well as relating structural changes to variations in chemical properties of the soil, Little *et al.* state that raindrop impact and crusting are particularly important processes in the reduction of infiltration of the soil where the mean stable aggregate size is < 1 mm diameter. In the experiments conducted on the New Marte samples, there are few water-stable aggregates larger than this threshold value, suggesting that infiltration will be impeded despite a larger pore network. The following chapter discusses a series of infiltration studies.

7 DIRECT MEASUREMENT OF WATER INFILTRATION AT NEW MARTE

7.1 INTRODUCTION

Whilst the soil structural measurements of the last chapter have attempted to show any differences in the characteristics of soil pores in the plot experimentation at the New Marte site, these measurements do not provide any direct indication of the soil's properties with regard to the infiltration of water. Infiltration is a factor which plays a key part in the hypothesis described and discussed in sections 1.3 and 6.1. This chapter examines the infiltration of water in relation to both soil conditions and to soil management at New Marte, specifically with relation to agroforestry.

7.1.1 Introduction to infiltration measurements

The limiting rate at which water infiltrates into the soil has been described as "the maximum rate at which water can be accepted by the surface without causing ponding or runoff" (MAFF/ADAS, 1982). Infiltration of water into soil is a particularly important process to quantify for both agronomic and pedological reasons.

Agronomically, knowledge of the rate of infiltration is a key factor in management strategies of soils and, if irrigated, of the water applied to them. The mathematical treatment of infiltration when the soil is saturated is associated with D'arcy's Law:

$$v = \frac{Q}{tA}$$

which can alternatively be written as:

$$v = \mathrm{K}\frac{P_1 - P_2}{s}$$

(D'arcy, 1856 - restated in these forms by Baver *et al.*, 1972)

where v is the average velocity of water over cross-section A, where flow is horizontal, Q is the amount of water transmitted in time t. This can be restated in terms of a factor K, known as the hydraulic conductivity with P_1 and P_2 the pressures of the inlet and outlet of a porous body of length s . The hydraulic conductivity (K) is calculated empirically and is a factor which combines several others affecting water flow, including the viscosity of the water and the tortuosity and size of channels in the soil matrix.

From a pedological viewpoint, the rate of infiltration will influence the quantities of water being transmitted down the profile. If the soil is incapable of accepting water, since the hydraulic conductivity of the soils least permeable layer has been exceeded, then ponding or runoff will occur, the latter possibly inducing physical movement of the soil material, *i.e.* erosion.

Because of this interest in water infiltration into the soil, particularly with regard to the management of irrigation water application, many models have been devised to predict infiltration characteristics using functions of other soil parameters. These models have themselves been derived either using empirical observations of infiltration as their starting point or using a theoretical model of the soil. Green and Ampt (1911) and Philip (1957) both created models based on simple sets of observable soil properties, whilst Horton (1940) used field data of directly measured infiltration rates as a starting point. Various reviews (*e.g.* Swartzendruber and Hillel, 1973; Hillel, 1982) have been made of these and other models and equations. In semi-arid rangeland environments, Horton's model has been found to be the "best fit" in comparative data analyses between these models (Gifford, 1976). Horton's model produces the following equation:

$$i = i_c + (i_o - i_c)e^{-kt}$$

where i is the infiltration rate, i_c, i_o and k are constants and t is time elapsed.

This exponential decay function, with three unknown constants, requires empirical infiltration data at specific times in order to be solved. At t = 0 the infiltration rate $i = i_o$. The constant k is the determinant in how rapidly the infiltration rate i changes from i_o to i_c, which is the steady state infiltration rate. The field data used by Horton show, on average, a decrease in infiltration to a steady state after a period of 2 - 3 hours. Horton considered that factors on the surface of the soil were largely responsible for this reduction. These factors included swelling of soil particles and the collapse of small pores, which together both lead to ponding.

With detailed knowledge of both the infiltration rate and the hydraulic conductivity of each horizon within a soil profile it is possible to construct a further model (*e.g.*

Bouma and Wösten, 1979) to describe soil water movement down the profile. However, in soils that swell, such interpretations are complicated by the effect of surface ponding. Collis-George and Laryea (1971) demonstrated that the rate of water entry into such soils was greater when the soil was not ponded. This implies that measurements of infiltration rates in soils that swell will underestimate the infiltration possible when the soil surface is subjected to steady rainfall, rather than the ponding conditions generated in the infiltration measurement. This factor is not restricted to smectite-rich tropical soils; Messing and Jarvis (1990) found significant variations due to swelling in the overall transmission of water in temperate soils which did not contain any smectitic clay minerals.

Just as there are many different theoretical and empirical models of water infiltration, measurement of the infiltration rate into the soil has been attempted by many different methods. These have ranged from detailed laboratory experiments trying to validate the theoretical models of water transmission, to general methods suitable for field use. Almost all methods are empirical, relying on some means of observing water entering the soil. The methods available have been reviewed (Youngs, 1991), varying in the method of applying the water to the soil from simulated rainfall (*e.g.* Amerman *et al.*, 1970) to direct application of water at different tensions using tension infiltrometers (*e.g.* Messing and Jarvis, 1993). The most common method is to flood a small area of soil and observe the rate of infiltration by direct measurement using ring infiltrometers. The use of a double ring infiltrometer has become a standard procedure (Landon, 1991) and this method is both endorsed by soil science organisations and described in detail in many sources (USDA - Black, 1965; MAFF/ADAS, 1982; USDA - Klute, 1986; TSBF - Anderson and Ingram, 1993). This method has been used for the measurements described in this chapter.

7.1.2 Relationships with other soil measurements

The direct measurement of water infiltration in various soils and in various conditions at the New Marte experimental site has been made in order to link this with the descriptive soil structural measurements (sections 5.1, 6.1 and following). This linkage between the influence of soil structure and water infiltration is a central part of the main hypothesis of the agroforestry experimentation (section 1.3.2) and is integral to the discussion later in this thesis. The soil structure information has been collected in a variety of forms (bulk density, porosity, penetration resistance, particle size analysis, aggregate stability and meso-pore size distribution analysis) and at a variety of levels (plot level, site level). Since the most detailed work has been undertaken at the plot level, this infiltration experimentation has been based at the plot level too. In order to couple these soil structural data collected at New Marte with information on the infiltration rate of water into the soil, two experiments linking the former with the latter were undertaken.

Whilst undertaking the infiltration measurements, a number of other soil structural measurements were made in addition to those already made at the plot level. These further allow for comment and comparison with the infiltration measurements. Additionally parameters have been recorded that allow a check on the procedure adopted to be made, these may also allow various anomalies, such as faunal burrows to be spotted.

7.1.3 Rationale for experimentation

It has been stated (Hillel, 1982) that there are four major factors which influence the infiltration rate of a particular soil. These are:

a) the length of time that the soil experiences rainfall, infiltration rates appear to usually decrease with time;
b) the soil surface conditions, including structure and texture;
c) the hydraulic conductivity of the various horizons of the soil profile;
d) the initial water content of the soil.

Since all of these factors will vary at the New Marte site throughout the field season, consideration of each of these in relation to the field programme has been made.

During the rainy season at New Marte, individual rainfall events may be very short in duration but very intense (*e.g.* July 1994: average rainfall 5.70 mm per event, range 0.2 mm to 30.5 mm). These events are likely to lead to surface ponding and the disturbance of weak soil surface structures. Therefore both the initial and steady-state (if reached) infiltration rates are important parameters for consideration and comparison with the structural measurements.

The soil's structure not only determines the total porosity but also the shape, size and tortuosity of the pores. These all influence the transmission of water through the soil. Apart from the swelling of the soil and the loss of small pores, the surface soil structure may also collapse to form a crust, or may otherwise slake, capping the soil surface. The influence of such crusting, particularly under the impact of raindrops, has long been recognised (*e.g.* McIntyre, 1958). Given that the surface texture of the soils at New Marte ranges from sandy to clay-rich extremes, and that a standard practice in the field preparation when weeding the plots is to disturb the soil surface with an adze-type hoe the experimentation has taken these into account selecting sampling positions in the two textural extremes and including a hoeing field treatment.

The hydraulic conductivity of the soils at New Marte will obviously vary considerably between the sandy textured and the clay-rich soil horizons. Where infiltration measurements have been made in positions where there is an overlying sand-rich layer, measurements of both the depth of the sandy layer and the depth of wetting have been made after the infiltration experiment.

The initial water content of the soil will vary greatly at New Marte depending upon the time of the year relative to the rainy season. Since the interest in trying to manage organic matter inputs into the soil is aimed at influencing infiltration, then the rainfall events which are most important are those that occur early in the rainy season, before the site is flooded. After this time, the ponded infiltration will be dependent upon the hydraulic conductivity of the underlying soil horizons and sedimentary strata. Therefore, in order for the infiltration measurements to represent the early rains, they need to be made with dry season surface conditions.

7.2 EXPERIMENTATION

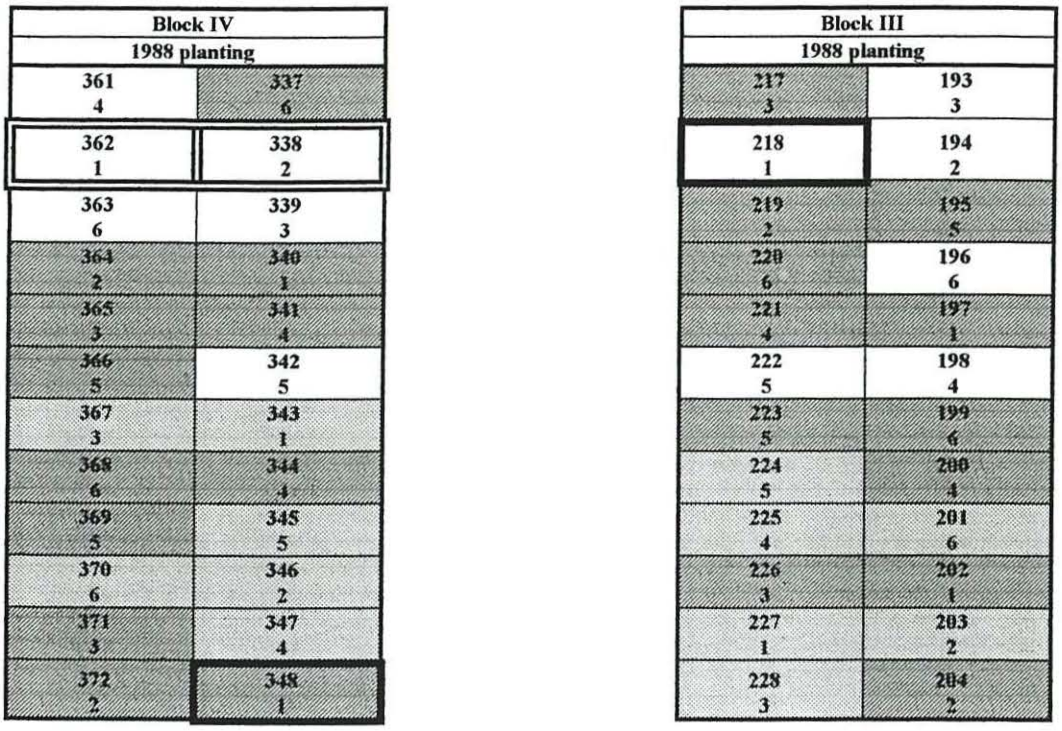
7.2.1 Introduction

Two connected experiments were undertaken, in order to make objective statements with regard to the effect of trees on the infiltration of water into the soil beneath them and to compare different soil types. The first experiment investigated the relationship between the infiltration rate at a given point and the radial distance of this position from an individual tree. The second considered the effects on the infiltration rate of i) the surface soil structure and ii) cultivations undertaken within plots.

7.2.2 Experiment 1: relationship of distance from tree to water infiltration

The potential influence of a tree on the infiltration characteristics may be considerable due to development of a litter layer, organic matter inputs amending soil structure and physical alteration of the soil by tree roots. Because the experiment designed to investigate this was undertaken in February 1995, after many of the other intensive plot experiments, great care was required in selecting suitable sampling locations. The criteria were that the plot should have been disturbed only minimally and not have been subjected to any intensive invasive activities such as root coring or tree pruning. On this basis the plots available were 194 and 338. Two *Acacia nilotica* trees were selected from one of the unpruned plots (Figure 7.1) on the basis of each being uniformly influenced by near neighbours (either as a tree on its own and not being influenced, or having uniform neighbouring trees) and by the uniformity of the surrounding soil surface. Since plot 194 has a very variable surface texture, plot 338 was selected.

Figure 7.1 Plot Treatments



Key

1	Control plot	4	*Acacia senegal*
2	*Acacia nilotica*	5	*Balanites aegyptiaca*
3	*Acacia seyal*	6	*Prosopis juliflora*
(shading)	Pruned trees	(shading)	sorghum intercropping
(double border)	Plots used in Experiment 1 infiltration studies	(thick border)	Plots used in Experiment 2 infiltration studies

Two randomly allocated radial axes (from eight cardinal (¼π) axes) from each tree were marked (e.g. NE and W) and infiltrometer measurements were made at positions representing mid-canopy, canopy edge and away from canopy (at 1 m, 2 m and 3 m) along the two axes (figure 7.2). Plot 362 (neighbour to 338) was used as a control plot in order to differentiate between a tree plot and a no tree plot. Six infiltration measurements, on the equivalent of two radial axes in plot 338, were made in the central area of plot 362, away (>10 m) from the influence of the trees of neighbouring plots. The size of the neighbouring trees in the plot and the positioning of the infiltrometers is displayed in figure 7.3.

Figure 7.2 Sampling Locations - positions relative to trees

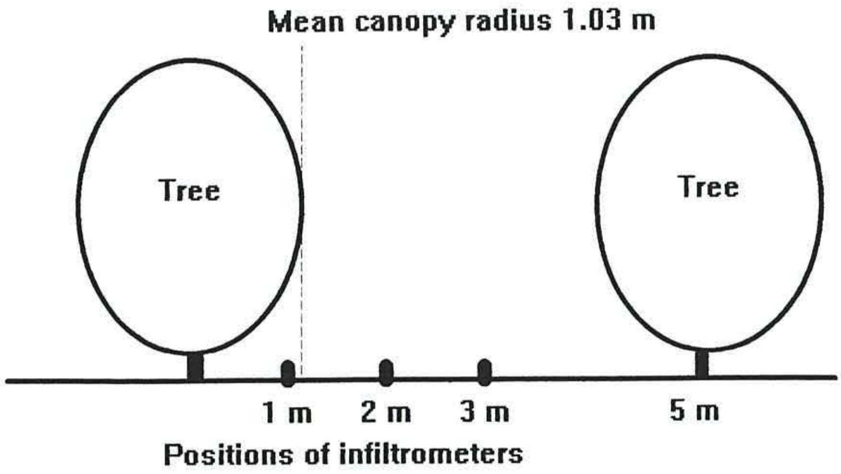
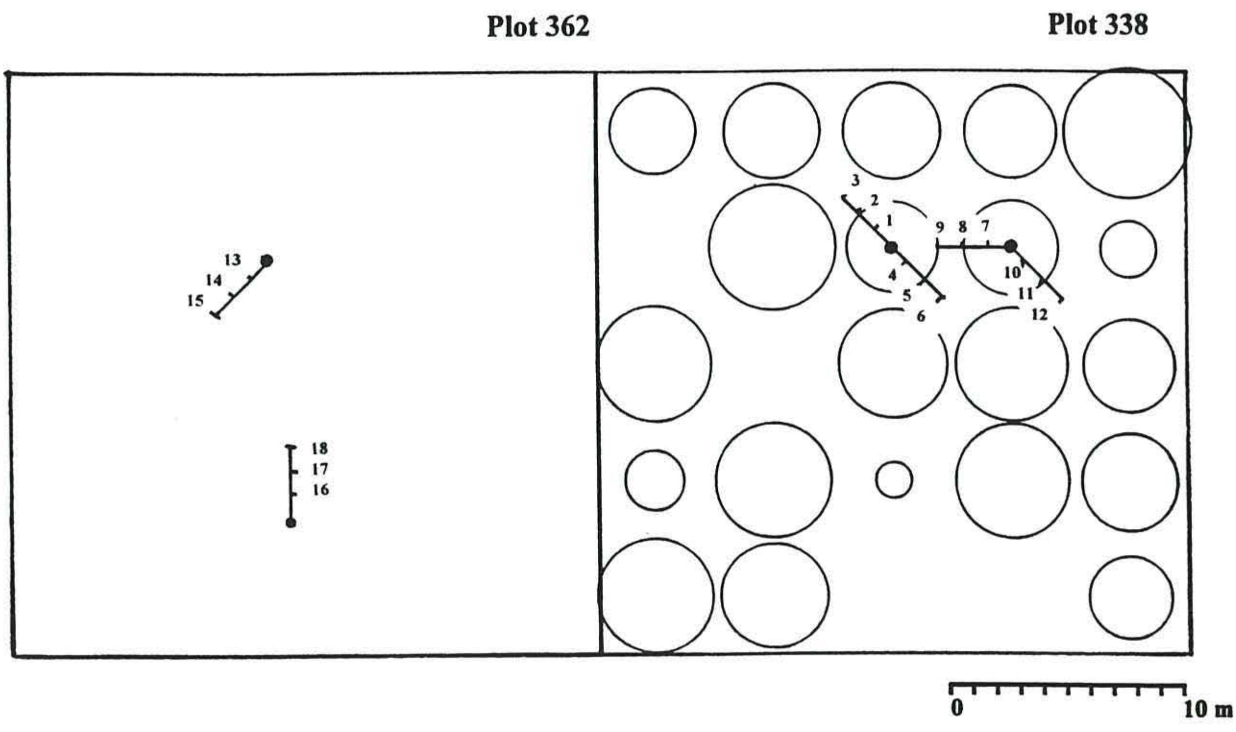


Figure 7.3 Location of the infiltration measurements relative to the trees in plot 338 and in control plot 362



7.2.3 Experiment 2: Comparison of water infiltration at different locations at New Marte

In this experiment it was intended to identify the differences in infiltration rate between locations with differing surface soil texture and between cultivated and non-cultivated areas at these locations. Two control plots 218 and 348 (figure 7.1) were identified as representing respectively a sandy soil surface and a clay soil surface. Within these plots two areas (a & b- each 5 m x 5 m) were selected, each having a near uniform soil surface representative of the plot (see figure 7.4). These two locations were divided into four quarters (2.5 m x 2.5 m) along W-E and N-S axes (figure 7.5). The positions and their treatments for the individual infiltration measurements, are given in table 7.1. The NE and SW quarters were cultivated by hoeing, the normal dry season weeding method, whilst the NW and SE quarters were left undisturbed as at the end of the 1994/5 field season; within each of these (2.5 m x 2.5 m) areas an infiltration measurement was made. Therefore this experiment involved 16 infiltration measurements:

sand/clay extremes of soil surface
Two locations within each plot
cultivated/undisturbed soil surface at each location
Two replicate measurements at each location/surface combination

Table 7.1 Key to sampling locations (infiltration experiments i19 - i34)

	Area a		Area b	
Plot	cultivated	not cultivated	cultivated	not cultivated
218	i20, i21	i19, i21	i24, i25	i23, i26
348	i28, i29	i27, i30	i32, i33	i31, i34

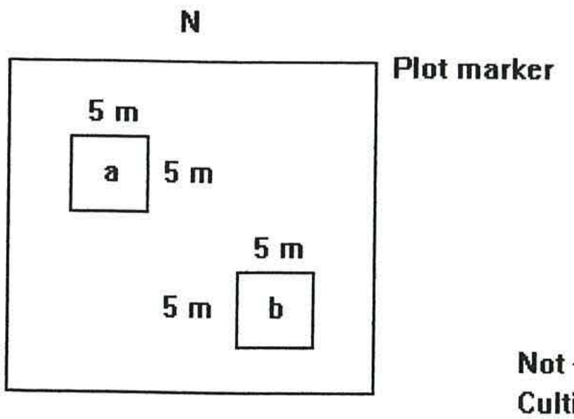


Figure 7.4 Two areas per plot

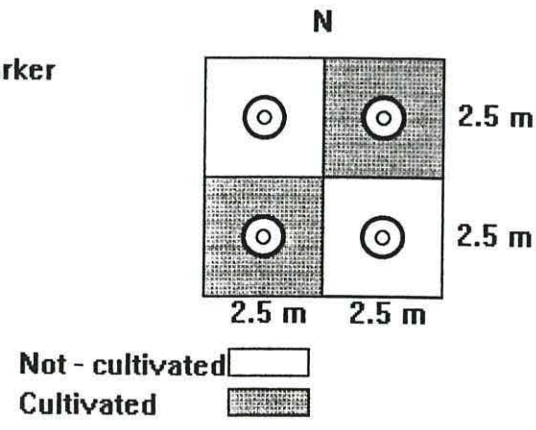


Figure 7.5 Cultivated and not-cultivated surfaces in each area

7.3 METHODS EMPLOYED - MEASUREMENTS MADE IN INFILTRATION EXPERIMENTS 1 AND 2

7.3.1 Equipment

The method adopted for the ring measurements follows the standard procedure given by Landon (1991). Four sets of double-rings were used in the measurements. These had pairs of radii of 25 & 52 cm, 27 & 55 cm, 29 & 59 cm and 30 & 61 cm. The last three pairs had been purchased, but the fourth pair, the smallest, was fabricated in Nigeria. The different ring sizes allow the rings to be packed together for transportation and storage. The infiltration measurements were made in sets of three or four. In Experiment 1, where three rings were used for each radial axis from the tree, these were conducted simultaneously. In Experiment 2, where there were four measurements per 5 m x 5 m block, the infiltration measurements were undertaken in sets of four.

For each infiltration measurement a set of associated soil structural and soil water characteristics was assessed (see plates 7.1 and 7.2). These were in addition to the soil structural parameters recorded over all of the intensively studied plots (see section 1.1). This creates a data set allowing the correlation of results required to associate the following soil structural properties, both measured and derived, with infiltration measurements.

$\Theta_{m(i)}$ ***Gravimetric soil moisture content (10 - 15 cm below surface) - initial***
Sample taken (same sample as for bulk density) weighed in the field state and after oven drying at 105°C

$\Theta_{m(f)}$ ***Gravimetric soil moisture content - final***
Sample taken at 10-15 cm after infiltrometer run, weighed in the field state and after oven drying at 105°C

BD ***Bulk density at 10-15 cm below surface level***
Sample of known volume taken in a *p*F ring, dried and weighed. The measurement of bulk density was made at a fixed depth of 10-15 cm to avoid the influence of the surface cultivation.

ρ ***Porosity***
Calculated from bulk density and assumed density of soil matrix components

% wsa ***Aggregate stability***

Sample taken before infiltrometer run. Aggregate stability measured using the wet sieving procedure described in section 6.6

After the infiltrometer run, three further measurements were made:

d_w ***Depth of wetting***

d_s ***Depth of sand layer***

d_i ***Depth of ring insertion into soil***

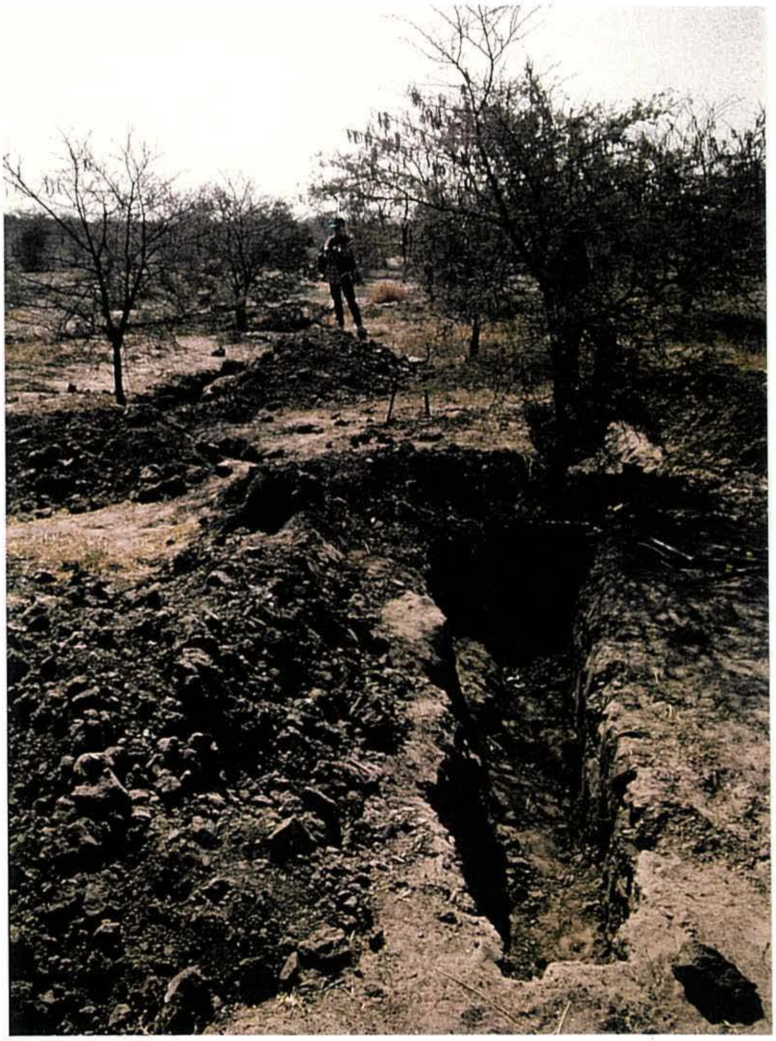
7.4 RESULTS

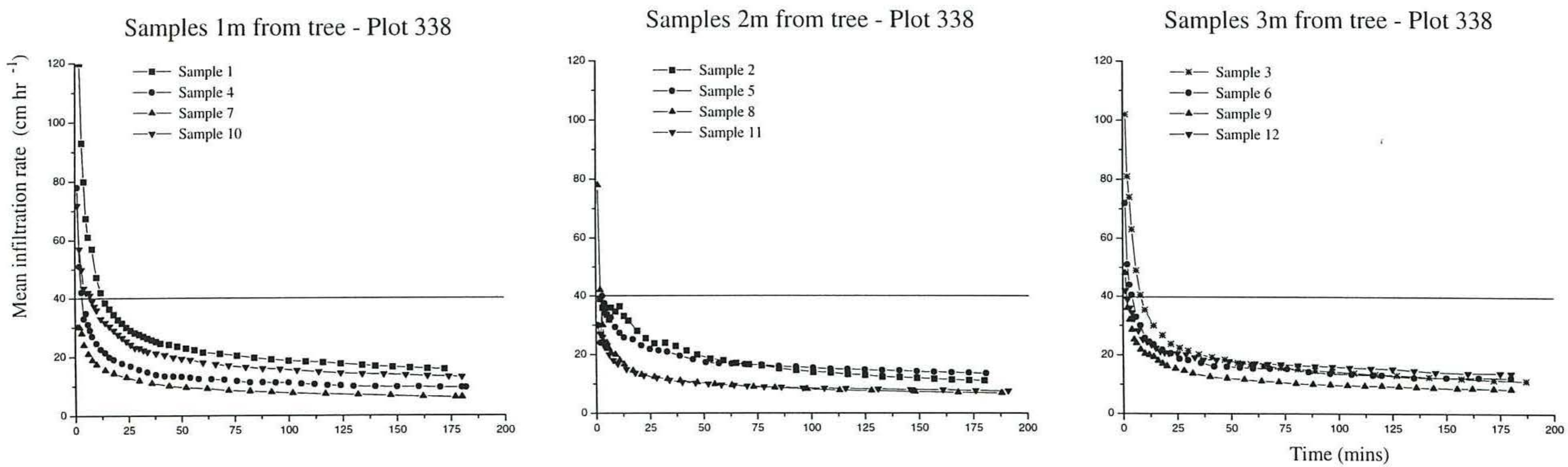
7.4.1 Infiltration Experiment 1

The results from the measurements made in this experiment are shown in figure 7.6. This figure shows the results plotted as infiltration rate *vs.* time as a series of graphs: measurements made in plot 338 at 1 m, 2 m, and 3 m radial distances from the trees and the measurements made in the control plot 362, at 1 m spacing on two linear transects. Sample numbers refer to those shown in figure 7.3.

Plate 7.1 (above): **Depths of wetting and friable sand measured after infiltration rate measurement has been made.**

Plate 7.2 (right): **Trenches dug to facilitate measuring depth of wetting and friable sand. These trenches indicate the radii from the *A. nilotica* trees along which the measurements were made.**





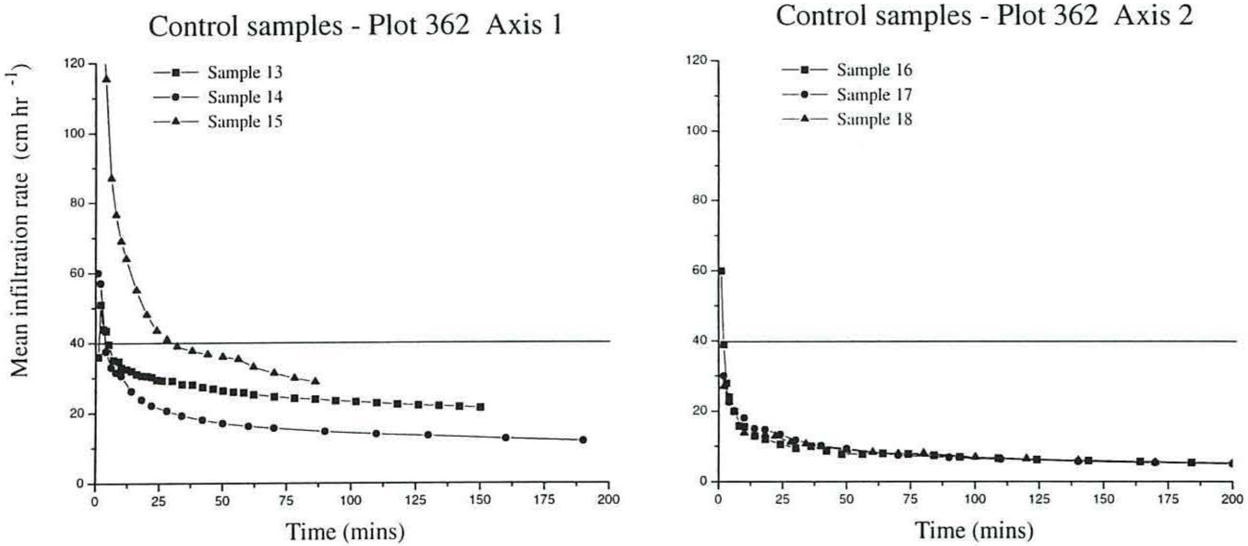


Figure 7.6
Results of infiltration experiment 1.

Data from plot 338 grouped into radial distances from trees
Data from plot 362 (control i.e. no trees) grouped into the two linear axes sampled

Line at Infiltration rate = 40 cm hr^{-1} plotted to allow comparison between graphed data

7.4.2 Statistical analysis

The decay-curves of the infiltration measurements from relatively large initial values to smaller and more constant values present particular difficulties when quantitative information from these curves is sought. Whilst it is possible to fit an exponential or polynomial decay function to each graph, it is clear that no single type of mathematical function could be used for all of the decay-curve results. This would introduce another complexity to interpreting the results. Therefore, the graphical results gained from the infiltrometer measurements have been analysed by identifying three parameters which can be derived from the measurements alone without fitting a mathematical function to them.

The three parameters used in the statistical analysis of the measurements are:

TI30

Total infiltration in the first 30 minutes. This has been calculated by integrating beneath the a line fitted (point-to-point) between the values covering this period (*i.e.* 0-30 minutes inclusive).

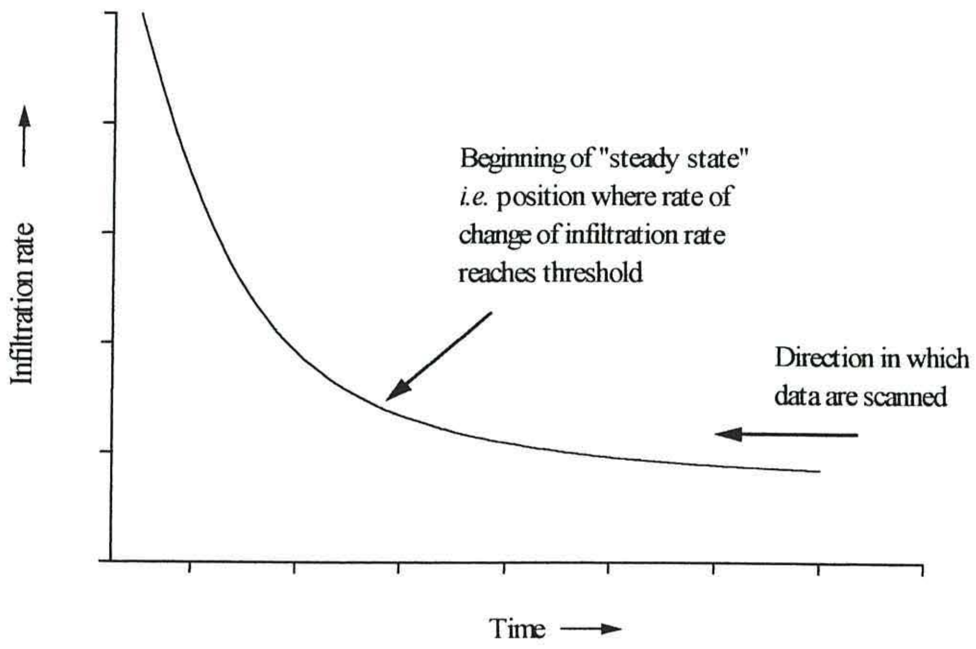
SSIR

The mean steady state infiltration rate after 170-210 minutes. This window has been set to encompass the 3 hour mark (180 minutes) but to eliminate the experiments (13 & 14) that did not reach steady-state.

TSSI

Time to reach steady-state infiltration. This is a derived variate because it arbitrarily defines "steady-state". It has been calculated by taking the second differential of the difference between adjacent values and then locating where this reaches a value beyond a defined threshold. This last step involves taking "the longest time period" at which a measurement was made as its first value, then scanning the data to the next longest time; the position when the differential exceeds a threshold value for the differential is considered to be the time at which steady-state occurs (figure 7.7)

Figure 7.7 Detail of how the differential rate of change of infiltration was used to find the time to reach steady state infiltration



7.4.3 Statistical testing

The three parameters (*i.e.* TI30, SSIR, TSSI) have been tested for variations both (i) with the radial distance from the tree and (ii) as a comparison between those experiments associated with trees and those in the control plots. The results of these tests are respectively shown in tables 7.2 and 7.3. Note that in order to complete the test between the tree and control experiments the division between plots has been removed from the analysis in order to complete the test using the limited number of residual degrees of freedom available. The two plots are physically adjacent and such a move was considered justified.

It is possible to create a new allocation for the relative positioning to a tree of each experiment based not on the radial position to the two trees selected but relative to the canopy extent of all trees in the plot. This is shown in figure 7.3 which maps the mean crown radii of the trees in this plot and is overlain with the positions of the infiltrometers. However, this re-allocation makes no difference to the results of the statistical tests, there is still no detectable significant ($P<0.05$) difference attributable to the position relative to the trees.

Table 7.2 Comparison of Tree *vs.* Control samples ‡

		Residual degrees of freedom	Mean for tree samples	Mean for control samples	sed	Test for significance (P<0.05)
TI30	Total infiltration in first 30 minutes	14	9.15	10.09	2.15	ns
SSIR	Mean infiltration at steady state (170 -220 mins)	12 †	10.79	6.88	1.89	*
TSSI	Time to reach steady-state infiltration	14	16.75	17.1	3.81	ns

Table 7.3 Comparison of effect of radial distance from tree

		Residual degrees of freedom	Mean for samples at 1 m distance from tree	Mean for samples at 3 m distance from tree	sed	Test for significance
TI30	Total infiltration in first 30 minutes	14	9.67	9.18	2.15	ns
SSIR	Mean infiltration at steady state (170 -220 mins)	12 †	11.08	11.43	1.64	ns
TSSI	Time to reach steady-state infiltration	14	20.3	17.1	3.82	ns

ns not significant at P. <0.05

† Note that two measurements did not reach steady-state

‡ Note that the between plot difference has been removed from the analysis model and the sample is considered to have originated from one plot only - plots are adjacent

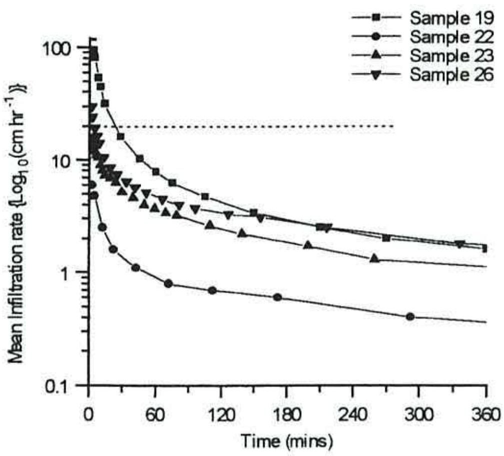
7.4.4 Experiment 2 Results -Comparison of water infiltration at different locations at New Marte

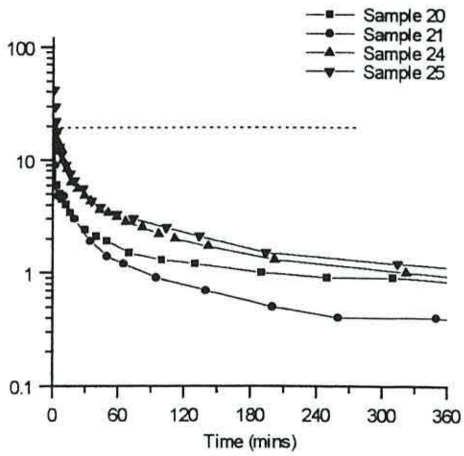
This experiment is concerned with two factors: the tillage of the soil surface and the location of the plot: either sand-rich surface or clay-rich surface. The results of this experiment are presented in figures 7.8 and 7.9

Figure 7.8
Infiltration experiment 2 results
Plot 218 surface not cultivated

Figure 7.9
Infiltration experiment 2 results
Plot 218 surface cultivated

Infiltration rate = 20 cm hr $^{-1}$ marked to allow comparison





These show only the results from the plot with a sandy surface (Plot 218). The clay-rich plot (Plot 348) results are not shown because no steady-state infiltration was achieved in any of the experiments conducted on this plot. All of the experiments on plot 348 experienced catastrophic infiltration: for example, during the first minute one of the experiments took >30 dm^3 of water without reaching steady-state. This was due the presence of deep vertisolic cracks in the soil. These cracks were not noticeable at the soil surface until after the penetration of water through them. An example of these cracks is shown in Plate 7.3. In terms of water infiltration during rainfall events, these cracks will obviously play a very important rôle in the initial infiltration of water to the soil and into the uppermost aquifer. The profile conditions at New Marte suggest that these cracks extend to the sandier layers beneath the clay and therefore suggests that this method of water transmission will be a major component of ground-water recharge. The swelling of the clay body will eventually close these deep vertically-oriented cracks and the surface will then flood, the ponded infiltration rate will then become the determining factor for water penetration into the soil and for ground-water recharge.

Because of the lack of quantitative information from the experiments in plot 348, there is only just enough replication for testing the part of this experiment concerned with tillage of the soil surface. These results are shown in table 7.4.

Table 7.4 Comparison of cultivated *vs.* not cultivated surface soils in measurements from plot 218

		Residual degrees of freedom	Mean for cultivated samples	Mean for undisturbed samples	sed	Test for significance
TI30	Total infiltration in first 30 minutes	5	3.43	1.89	1.68	ns
SSIR	Mean infiltration at steady state (170 -220 mins)	5	1.55	1.35	0.58	ns
TSSI	Time to reach steady-state infiltration	5	16.95	9.40	10.50	ns

Key

ns not significant at P. <0.05

Plate 7.3 (left) **Cracks in soil surface revealed after attempted infiltration measurement in plot 348**

Plate 7.4 (below) **Area to the south of New Marte field site - flooded during the 1994 rainy season**

7.4.5 Results - Other measurements:

The other measurements made for each individual infiltration experiment included the measuring the depth of wetting and the depth of sand in a section dug after the experiment along the radial axis of the measurements (see plates 7.1 and 7.2). From Experiment 1 these measurements are presented in figure 7.10 for samples from both plot 338 with trees and from control plot 362.

In addition to the depth of sand layer and the depth of wetting in these transects the results of the measurement of soil physical conditions (*e.g.* bulk density, aggregate stability) are shown in table 7.5. For these and the depth of sand measurements, it is unfortunate that although they may relate to the "infiltrability" of the soil (*i.e.* part of the hydraulic conductivity factor K) there is insufficient replication of the experiments to use these subsidiary measurements as a set of co-variates in the statistical analyses of the main infiltration parameters as presented in section 7.4.2. However, they may reveal contrasts both between experimental plots and the variates themselves.

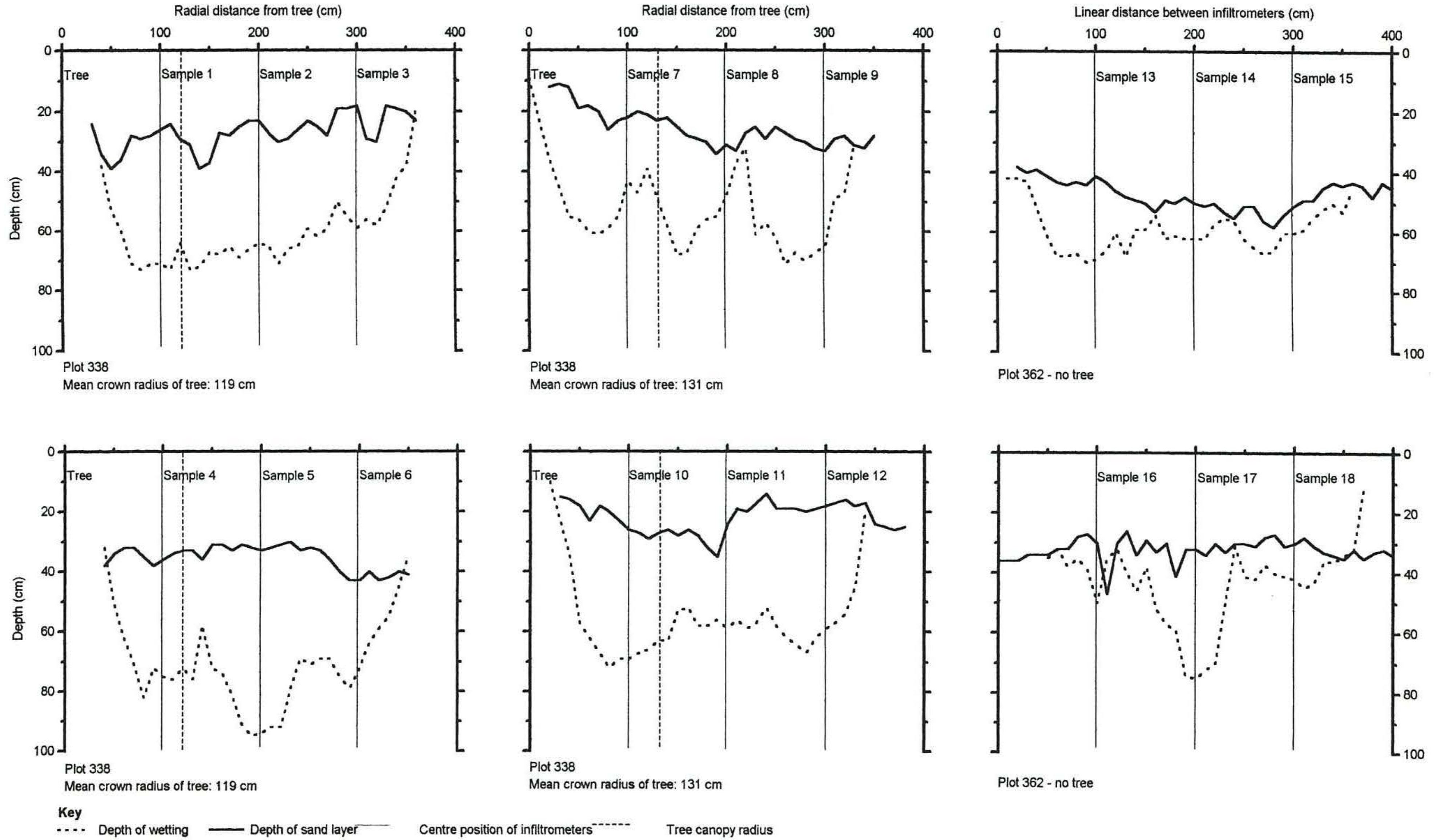
Additionally, other measurements which do not relate directly to the soil conditions but are factors in the overall functioning of the experiment, such as the depth of ring insertion, have been used to check on the procedure. These results are also shown in Table 7.5

Table 7.4 Results of other measurements made on infiltration samples

							Dry sieving			Wet sieving									
										0.5 mins		1.0 mins		2.5 mins		5.0 mins		10.0 mins	
Experiment	Infiltration sample	Treatment	Depth of ring insertion	Bulk density	Moisture content - before	Moisture content - after	>5600 um	5600 um - 2000 um	<2000 um	1400 um	500 um	1400 um	500 um	1400 um	500 um	1400 um	500 um	1400 um	500 um
			cm	g/cm3	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1	1	t1	11	1.84	6.8	12.8	0.0	20.2	79.8	41.6	4.2	37.8	3.2	38.6	3.2	34.8	2.8	26.2	4.4
	2	t2	11	2.07	0.7	11.7	0.0	16.1	83.9	16.4	3.8	16.6	3.4	14.4	3.0	15.8	2.4	13.4	2.8
	3	t3	11	2.19	0.5	10.0	0.0	20.4	79.6	15.6	2.6	13.2	3.2	2.4	1.4	15.8	2.4	11.4	2.0
	4	t1	11	1.94	0.2	12.1	0.0	12.5	87.5	19.8	1.4	14.6	2.6	14.0	1.6	12.8	2.6	12.0	2.4
	5	t2	10	1.75	0.2	13.3	0.0	11.9	88.1	18.0	2.2	20.6	3.4	18.4	2.6	17.0	2.2	14.6	1.6
	6	t3	11	1.92	0.3	12.8	0.0	14.0	86.0	24.8	2.8	25.2	3.2	29.2	3.0	26.2	3.6	23.8	2.8
	7	t1	10	1.98	1.3	15.2	0.0	25.0	75.0	27.4	2.6	34.4	2.6	17.2	3.8	15.0	2.6	16.0	2.8
	8	t2	10	1.78	0.6	14.7	0.0	21.1	78.9	18.0	1.4	12.6	2.4	12.6	3.0	11.4	2.6	7.0	2.4
	9	t3	10	1.90	0.4	11.7	0.0	15.9	84.1	11.8	2.4	11.0	2.8	9.2	2.4	10.4	2.2	8.4	1.8
	10	t1	13	2.19	0.2	12.4	0.0	18.0	82.0	17.6	6.4	11.0	2.8	11.4	2.4	9.2	2.0	9.6	2.2
	11	t2	11	2.11	0.2	14.0	0.0	16.1	83.9	15.8	3.4	14.2	3.2	9.8	3.4	10.8	2.8	10.4	2.8
	12	t3	10	2.17	0.6	14.4	0.0	21.2	78.8	34.2	2.8	23.4	4.2	20.0	3.8	14.2	3.2	17.8	3.0
	13	nt	10	2.09	0.3	9.2	0.0	17.9	82.1	39.6	2.6	36.2	2.8	30.0	3.2	24.0	3.0	20.6	2.8
	14	nt	10	2.16	0.2	14.9	0.0	11.8	88.2	35.8	1.0	31.0	2.0	27.0	3.0	20.8	3.4	16.0	3.0
	15	nt	10	1.78	0.1	17.8	0.0	13.3	86.7	43.2	2.0	34.2	3.0	29.6	4.0	20.6	4.2	15.4	3.8
	16	nt	10	1.78	0.4	14.8	0.0	17.0	83.0	19.2	3.4	19.4	2.8	18.4	3.2	13.6	2.8	10.4	3.0
	17	nt	10	1.52	0.4	15.2	0.0	15.2	84.8	31.6	2.6	21.4	4.0	17.6	4.8	14.6	4.0	12.4	4.0
	18	nt	10	1.62	0.5	14.7	0.0	16.9	83.1	19.8	3.8	17.6	4.6	17.4	4.0	12.6	3.6	13.0	3.6
2	19	nc	8	2.29	3.3	20.8	27.3	22.2	50.5	11.4	3.8	4.8	5.2	3.2	4.2	1.8	4.2	1.4	3.4
	20	c	10	2.21	1.8	20.3	34.5	22.9	42.6	5.0	3.8	3.6	4.2	2.8	4.6	2.0	3.4	1.8	3.8
	21	c	8	1.79	2.8	17.9	21.0	23.0	56.0	6.4	3.6	4.0	2.6	3.4	2.8	2.0	3.2	2.2	2.4
	22	nc	7	2.20	2.4	17.5	26.0	28.0	46.0	6.4	3.0	3.8	3.6	2.2	3.2	1.4	3.2	1.2	4.0
	23	nc	9	1.98	2.3	15.6	0.0	27.8	72.2	9.4	3.4	8.6	4.8	7.6	5.0	6.2	4.8	5.6	5.4
	24	c	10	1.90	0.6	15.8	0.0	26.6	73.4	5.0	1.6	4.0	2.6	4.0	2.4	2.4	2.2	2.6	2.2
	25	c	11	2.08	0.6	16.3	0.0	27.5	72.5	9.6	2.2	7.2	2.6	5.8	2.6	7.2	2.4	4.4	2.6
	26	nc	12	2.26	12.0	12.9	16.2	15.1	68.6	8.2	1.6	9.0	1.8	6.8	2.0	7.2	1.6	3.4	1.8
	27	nc	10	2.22	3.8	*	31.0	24.9	44.1	18.4	4.6	18.8	4.2	15.2	3.8	12.8	4.2	10.0	4.4
	28	c	11	1.85	3.1	*	43.0	16.5	40.5	17.2	4.4	19.0	3.6	18.6	3.4	17.2	3.6	13.6	4.0
	29	c	10	1.93	3.1	*	24.5	29.8	45.7	16.8	6.4	19.2	5.2	16.4	5.8	10.0	6.0	14.6	4.6
	30	nc	10	2.30	3.8	*	24.7	29.5	45.9	17.0	5.8	18.8	6.4	15.4	5.6	14.2	5.2	8.0	6.2
	31	nc	10	2.12	3.5	*	22.7	25.1	52.2	26.4	4.2	24.2	5.0	18.6	5.4	17.2	4.8	16.2	4.4
	32	c	10	1.82	3.1	*	21.5	24.8	53.7	22.2	6.6	22.6	6.2	21.8	6.2	20.2	5.8	15.4	5.8
	33	c	10	1.89	4.7	*	32.7	19.1	48.3	25.0	6.0	24.8	6.4	20.8	6.6	16.0	6.2	10.0	3.8
	34	nc	10	2.29	5.0	*	7.4	29.8	62.8	12.8	4.0	13.2	3.8	8.6	4.8	8.0	4.0	5.4	4.0

Key to experimental treatments			
Experiment 1			
	Radial distance		
	1 m	2 m	3 m
Tree	t1	t2	t3
No tree	nt		
Experiment 2			
Cultivated	c		
Not cultivated	nc		

Figure 7.10 Depth of wetting and depth of infiltration for samples in infiltration experiment 1



To investigate any relationship between the depth of sand layer and the depth of wetting along with the positioning of the infiltrometers, a comparison of the results presented in figure 7.10 has been made. First, to compare the relationship between the depth of wetting and the depth of the sand layer, a pairwise correlation for all pairs of values for these two measurements has been calculated. Second, an analysis between the position of the infiltrometers and the depth of wetting has been undertaken by comparing the mean values, over all positions, of the depth of wetting at positions directly under the infiltrometers (1 m, 2 m and 3 m radial distances; Figure 7.10) and for positions 50 cm (mid-point) from the infiltrometers (0.5 m, 1.5 m, 2.5 m and 3.5 m; Figure 7.10). The results for these two sets of analyses are shown in table 7.6.

Table 7.6 Statistical analysis of results shown in figure 7.10

Correlation			P<0.05
Depth of wetting *vs.* Depth of sand layer	r = 0.147	n = 199	*

	Depth of wetting directly under infiltrometers "under"	Depth of wetting at mid-points between infiltrometers "away"	sed	df	P<0.05
	(cm)	(cm)			
Mean	63.1	52.6	4.85	38	*
SD	9.75	12.12			
n	18	22			

7.5 DISCUSSION

There is obvious non-quantifiable evidence of the extreme differences in the infiltration rates witnessed between the parts of the site that have a sand-rich surface and those that have a clay-rich surface (see plot to plot textural comparison in chapter 5). The experiments in the clay-rich parts, with their very rapid infiltration, emphasise the influence of the large scale features on these soils, specifically the polygonal cracking. All of the soil structural measurements have been made during the dry season. Therefore to facilitate contrasts and comparison, these infiltration measurements were also made during the dry-season (February, 1995). However, when the site is flooded (see plate 7.3) the infiltration rate on these clay soils is severely reduced. This reduction is predominantly due to the swelling of the smectites in the soils' clay fraction coupled with the effect of slaking. The resulting solid, massive soil structure and expanded clays presents a barrier to further infiltration and therefore the ponded infiltration rate will be much reduced relative to that of initially dry soil conditions.

Examination of the other measurements (Table 7.5) made at the sampling locations of these infiltration measurements reveals some interesting comparisons. The bulk density measurements show no trend between either plot location or treatment applied, this follows observations made across the site (section 4.4) which suggested that the more massively structured sand-rich soils and cracked dry clay-rich had overall similar bulk densities. Therefore no trend emerges between bulk-density and any other variate of interest.

The data presented in figure 7.10, showing the depth of wetting, sand layer and the positions of the infiltrometers reveal two important results. First the depth of wetting is significantly ($P<0.05$) greater directly under the infiltrometers than in the positions either side of them (Table 7.6). Figure 7.10 shows that the depth of wetting beneath the central infiltrometer in the transects from samples i4, 5, 6 and i16,17,18 is much greater than for the outside infiltrometers. This suggests that there is considerable horizontal water movement from the outside (samples 4,6 and 16,18) infiltrometers, which given that the initial moisture content of the soils is low, could be expected. This will increase the time taken to reach steady state since water movement will be hemispherical rather than horizontal and planar as is envisaged in the methodology. Whilst a near constant (10 cm) depth of ring insertion was used for these experiments, a greater depth of insertion may have partially overcome this effect.

Second, there is a weak ($r = 0.147$), but significant ($P<0.05$), correlation (Table 7.6) between the depth of wetting and the depth of friable sand. This could be expected since water percolation is easier in coarser textured soil rather than a fine textured clay. In the sand-rich plots 338 and 362 the influence of trees, either directly (roots) or indirectly (meso-fauna) is seen in the differences in the depth of wetting relative to the depth of the sandy layer. Other possible causes of this distinction, such as differences in the amount of water applied in the infiltration experiments have been considered and eliminated. The influence of the strength of the soil, as measured in the penetration resistance (section 5.3.3) of the soils is not seen in Experiment 1. The penetration resistance measurements however, have shown only relatively small differences between plots 338 and 362.

Comparing the dry-sieved aggregate size distribution with the depth of friable sand reveals that the larger size fraction of aggregates appears where there is little sand coverage *i.e.* in a clay-rich position. The measurements made of aggregate stability, expressed as percentage water stable aggregates, reveals a distinct difference between the plots sampled. Plot 218 has very low values of water stable aggregates after 10 minutes wet sieving. This would suggest either a chemical interaction preventing strong aggregation or that the organic material available in this location has been oxidised. Whatever the cause, this low aggregate stability will result in rapid ponding of this location at the onset of the rains, with the resulting infiltration dependent upon the soils condition at depth rather than at the surface.

The influence of the trees on water infiltration can be divided into below-ground and above-ground. The below-ground influence is likely to be both physical and biotic. The increase in the pores, evident at the meso- scale (Chapter 6), is likely to influence porosity. However other features of the fabric of the soil are likely to be not so beneficial, particularly surface crusting from raindrop impact and from water flow over the surface. The mechanisms for crust development have been reviewed in the Sahelian context by Valentin (1992).

Above ground the raindrop impact will be altered by canopy interception of rain, with water reaching the soil through stem flow and leaf drip from the canopy. The size and force of impact of the raindrops reaching the soil has long been recognised as a factor in soil erosion and in crust development (McIntyre,1958), but only lately has the technology of measuring these reliably become available (Hall and Calder 1993).

The difference in the infiltration rates between "tree influenced" locations and "no-tree" locations is detectable (at $P<0.05$) in the mean steady-state infiltration rate, where overall there appears to be an increase in infiltration rate due to the presence of trees, with one of the parameters measured showing significant differences ($P<0.05$) between these different locations. These effects may include both above-ground and below-ground interactions. The total infiltration in the first thirty minutes and the time to reach steady-state infiltration did not reveal any significant differences between "tree influenced" and "no-tree" measurements. This might suggest that the tree effect, although evident in the steady state infiltration rate (SSIR), is not yet very pronounced since none of the other parameters (IR30, TSSI) showed significant differences (Tables 7.2 and 7.3). By contrast, from Experiment 2, the expected result - that a greater amount of infiltration would occur initially in soils where the surface is tilled and hence more permeable - was not found. This shows that in these particular soils (plot 218) surface structure does not constitute a barrier to infiltration, but that deeper structural features determine the net infiltration. With this knowledge, it is therefore unlikely that the effect of the trees will be evident in either the time to reach steady state or in the total amount in the initial 30 minutes of the measurements. With the effect of the trees limited to seven years, it must be concluded that longer periods will be required to detect any significant changes in soil-water dynamics.

8 EFFECT OF AGROFORESTRY TREE PLANTING ON ORGANIC MATTER AND NUTRIENT INPUTS TO THE SOIL AT NEW MARTE

8.1 INTRODUCTION

In semi-arid regions the factor most limiting to plant growth is the supply of water. In the two previous chapters the influence of soil structure, and the infiltration characteristics of the soil at the New Marte field experiment have been discussed. If sufficient water is available, however, other factors such as macro-nutrient and micro-nutrient availability to plants are likely to become limiting and although the aims of both the work undertaken within the project experimentation at New Marte and within this thesis have been focused towards the interplay of soil and water, it is also recognised that the rôle of agroforestry in semi-arid areas must include nutrient and soil fertility issues. Therefore, the aim of this chapter is to address some other plot-level interactions between the agroforestry planting and the soils found at New Marte. This also encompasses a small number of biomass and nutrient inputs which are then used within an example demonstration of the "Soil Changes Under AgroForestry" (SCUAF) computer model of Young and Muraya (1990) which aims to be applicable as a model of changes in two of the major plant nutrients (N and C) over periods of 10 to 20 years in response to different crop and tree management strategies.

The cycling of nutrients in tropical ecosystems has been extensively discussed (Russell, 1973) but, possibly because of the emotive influence of large-scale deforestation of Amazonia, there has been an emphasis on humid tropical forests (*e.g.* Jordan, 1985, Anderson and Spencer, 1991). In parallel with the trend away from intensive and high intervention farming strategies, the management of soil fertility through better resource management of crop residues and organic material is reflected in initiatives such as the TSBF programme. These have recently produced a number of studies focused on the "bio-mechanistic" processes influencing soil fertility (Woomer and Swift, 1994); this is in common with the growing number of long-term experiments on other tropical ecosystems, including those in parts of West Africa (Pieri, 1995; Brouwer *et al.*, 1992). The TSBF programme in particular, however, has devised a series of basic low-technology field methods and these form the basis of several of the methods adopted in this study.

There is much discussion of the dynamics of nutrient cycling at a variety of different spatial scales, in particular when the atmosphere-biosphere-hydrosphere continuum or "geoecosystem" (Huggett, 1995) is considered. In discussions of geoecosystems the concept of a piece of the land surface termed a "tessera" has been established (Jenny, 1965). A tessera (plural: tesserae) is an area (nominally 1 m^2) of the land surface embracing the soil pedon and other "soil-landscape" systems. The tessera extends downwards to the lithosphere and upwards to the biosphere (incorporating above- and below-ground nutrient dynamics) and the atmosphere. In this form, as described by Jenny (1965 - restated by Huggett, 1995), "tessera" is a useful term when formalising the processes and systems involved in the nutrient and biomass inputs to, and outputs from, a particular soil. The approach adopted has been to quantify the biomass inputs, and, using standard values for their nutrient content, enter these into the SCUAF model of nutrient cycling.

To complement the measurement of soil nutrients (Total N, Total P, Extractable P, % OM; see Chapter 5), a series of additional measurements quantifying organic matter inputs to the soil have been made. These measurements have again focused upon the eight plots studied in detail in chapters 5, 6 and 7 (Figure 5.1). Due to the logistics of the field experimentation and the importance placed on the soil structure measurements (Chapter 6) and soil-water processes (*e.g.* infiltration - Chapter 7), the aim of the work described in this chapter has not been a detailed study of nutrient chemistry processes, but rather to give an indication of the quantity and type of organic matter and nutrient inputs to the soil and their relationships, if any, with the planted trees.

8.2 METHODS

In designing the experimental methods and apparatus used, reference has been made to those of the TSBF as described by Anderson and Ingram (1993). In the spirit of this TSBF approach, much of the apparatus was constructed on site using locally purchased and recycled materials.

8.2.1 Litterfall

To assess the quantity of the organic material reaching the soil due to the presence of trees, the litter-fall from *Acacia nilotica* has been monitored using a series of litter traps. The design of the litter-traps is shown in figure 8.1 and their installation under trees in plate 8.1. The mouth of the litter collector has an area of 706 cm^2 (radius = 15 cm). The litter collector is raised above ground level, reducing the effect of termites consuming the collected samples, and with a "floppy" rather than rigid mesh bag where the sample is less likely to be blown out of the collector. These features may offer an improvement over the design described in the TSBF methods (Anderson and Ingram, 1993). The locations of the litter collectors, along with all other plot sampling positions, are shown in figures 5.2-5.9. Within the central 15 x 15 m area of each plot, twelve litter traps were installed. These were stratified such that four were placed randomly, surrounding two randomly selected trees, on the nodes of a 3 m by 3 m grid with 0.5 m spacing. The remaining four were randomly located on the nodes of a 1 m grid within the central plot area on positions not already allocated to soil samples and biomass boxes (see section 5.3.4). The litter-fall collectors were sampled seven times throughout the 1993/4 growing season.

At the end of the 1994/5 growing season, three specimens each of *A. nilotica* were plucked of their leaves from six areas of each tree crown. These samples along with stem samples and twigs were used for a parallel experiment at New Marte (unpublished ODA Project R4850 - final report, 1996).

Figure 8.1 Design of litter traps

Litter trap

Dimensions: ø 30 cm x (above-ground height) 60 cm
Hoop and upright: mild steel
Mesh bag: woven nylon

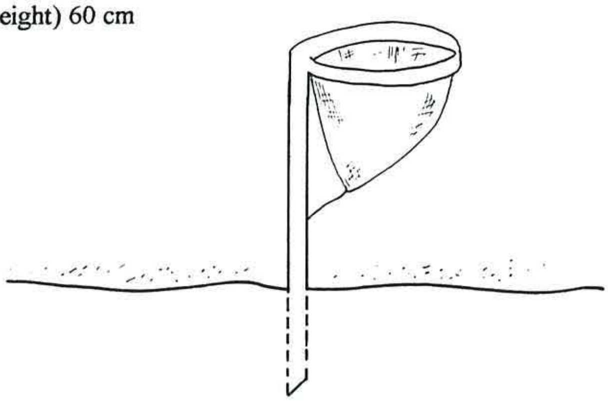


Figure 8.2 Design of throughfall and rainfall sampling apparatus

Rainfall collector

Dimensions: ø 22 cm x (above-ground height) 150 cm
Funnel: PVC
Bottle: High density polypropylene
(Mineral water bottle)
Bottle cover: ABS drainage pipe
Stand: Mild steel bar
Collector protected from birds using cocktail sticks

Throughfall collector

Dimensions: ø 22 cm x (above-ground height) 40 cm
Funnel: PVC
Bottle: High density polypropylene
(Mineral water bottle)
Stand: Mild steel angle
Funnel attached to bottle using elastic webbing

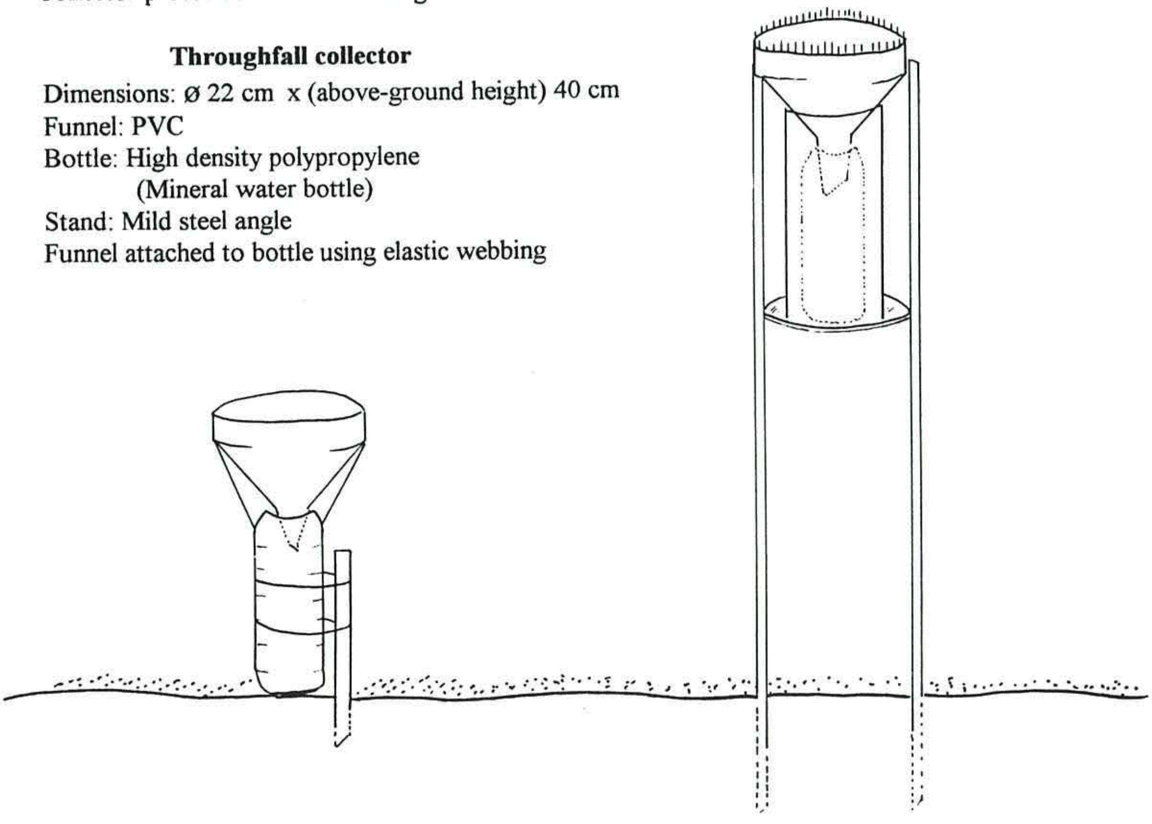


Plate 8.1 Installed apparatus under *Acacia nilotica* tree in plot 364

Plate 8.2 Mechanical coring for roots

8.2.2 Rainfall, Stemflow and Throughfall

Since the trees are in leaf throughout much of the rainy season, it is anticipated that the influence of the tree canopy on the chemistry of the water reaching the soil as throughfall or stemflow will be seen as increased concentrations of nutrients leached from the plant leaves and aeolian material washed off the plant. The chemistry of rainwater (without any direct influence of trees) is also likely to change throughout the rainy season because different air masses interact throughout this period (Hayward and Oguntoyinbo, 1987). For this purpose throughfall samples from the beginning and from the end of the rainy season have been collected and analysed along with rainfall samples collected throughout the rainy season.

The throughfall collectors were randomly allocated, but in a stratified system according to their relative positions to trees. In plots without trees (control plots) throughfall collectors were located at twenty randomly allocated positions on the nodes of a 1 m grid, not already used for soil measurements or for biomass decay experiment boxes. The positions of the throughfall collectors are shown in figures 5.2 - 5.9. In plots with trees, throughfall collectors were positioned at five randomly allocated positions on a 0.5 m grid within a 3 x 3 m square area around each of three randomly selected trees. Since 160 throughfall samplers were required, in order to monitor the same rainfall event over all eight plots simultaneously, the design of the sampling apparatus was as simple as possible using materials from local sources. The design of this and the rainfall sampler are shown in figure 8.2.

Additionally, three rainfall collectors of a similar design (Figure 8.2), but at 1.5 m above ground level, were positioned in the New Marte site weather station (50 m E of plot 1; see figure 1.18). Stemflow samples were collected as part of the parallel water-balance measurements at New Marte (unpublished ODA Project R4850 - final report, 1996), but these have not been analysed because of doubts of possible contamination from the materials used (ashphaltic roofing felt) for the sample collection.

Throughfall samples were taken twice during the 1993 rainy season (7 July and 7 October 1993). The volume of these samples was recorded in the field using graduated measuring cylinders. A representative sub-sample (15 cm^{-3}) was taken and stored in a sterile plastic specimen vial. To avoid microbial growth, these were kept dark and cool (*ca.* 17°C air-conditioned room) until being shipped to the UK for analysis. Similarly rainfall samples were collected each day after a rainfall event throughout the rainy season. All the samples (216 throughfall, 17 rainfall) were kindly analysed for seven elements (P, Ca, Na, K, Mg, B, Si) and for four ionic species (Cl^-, SO_4^{2-}, NO_3^-, NH_4^+), a total of 2563 measurements, using ICP-AES by staff of the British Geological Survey (Wallingford, Oxon.).

8.2.3 Standing dead material

The local farmers in North East Nigeria, who grow Masakwa sorghum on residual soil moisture, transplant their sorghum crops only after the flooding associated with the major rain events of the year have started to subside. Whilst this is essential, since sorghum cannot tolerate long periods of waterlogging, this delay also allows weed seeds to germinate with the initial rains and subsequently to be killed as the area floods. In this manner the flooding helps in the effort to keep the fields reasonably free of weeds which would compete with the sorghum crop for water and nutrient resources.

At the New Marte field site, extensive weeding was found to be required in order to plant the sorghum intercrop. Despite these efforts, volunteer plant species that grow on the residual moisture were found to remain as standing dead material at the start of the field preparations the following year. This material has been quantified since it has effects on both tree and crop planting and on system design, for whilst the design of a crop-tree system should minimise the effect of volunteer grasses, a silvi-pastoral agroforestry system may wish to focus upon these plants.

The mass of the plant material in an area (400 cm^2) directly above each of the soil sampling positions (Figure 5.2-5.9) was quantified from samples taken immediately before the soil samples were taken in June, 1993. In order to obtain samples of the same representative area for each point, a wooden quadrat of 20 x 20 cm with wide flanges was constructed and placed over the standing dead material, the quadrat was then used as a guide as the material was removed using a knife. This material was dried (70 °C) and weighed.

8.2.4 Biomass decay and herbaceous regrowth

In order to assess the rate of decay of plant material after weeding and to quantify the herbaceous regrowth thereafter, a series of ten biomass decay boxes was installed in each plot *i.e.* a total of 80 samples. Litter decay experiments are commonly conducted using "litter bags" where a quantity of plant material is placed inside a nylon mesh bag and a time series of measurements made on the mass of this material (Anderson and Ingram, 1993). In this instance it was found that ants and termites destroyed these bags and an alternative approach was adopted. The biomass boxes were constructed with PVC-coated wire mesh (2.5 mm aperture) sided frames, with a high-density polypropylene mesh base (10 mm aperture) (Figure 5.17). These boxes were affixed around quadrants marked and first sampled in September 1993. Throughout the 1993/4 growing season for the sorghum they were periodically sampled destructively for measurement of the above-ground biomass and, by volumetric coring, the below-ground (root) biomass. The boxes which remained in each plot were left untouched (*i.e.* not weeded) before being used for plant identification in January 1995 (section 5.3.4). The biomass boxes were positioned on randomly allocated nodes of the 1 m grid, at positions not already allocated to the soil sampling positions (Figures 5.2-5.9).

The above-ground biomass samples obtained were weighed fresh and after oven-drying (70 °C). The below-ground (root) biomass was obtained from the soil samples by hand-washing over a 500 μm mesh sieve. The material obtained was not separated into fractions and comprised of both roots and partially decomposed above-ground plant material. This was quantified after drying in the same manner as the above-ground material.

8.2.5 Below-ground stratigraphy of sorghum and tree root biomass

In a parallel large-scale project at New Marte during the 1994/95 field season (unpublished ODA Project R4850 - final report, 1996), a series of over 1200 soil cores (0-100 cm) were taken in sixteen plots across blocks three and four of the field experiment (Figure 1.18). Half of these cores were taken from the eight plots studied in detail in this thesis (Figure 5.1; see chapters 5, 6, and 7). These cores were taken to produce volumetric soil cores for studies of tree-crop root interactions. At the end of this field campaign in January 1995, a series of additional samples were taken to quantify the root biomass at different depths below-ground and these last results are considered in this section.

The positions of the 12 cores examined were determined by the experimental protocol adopted for the studies of the tree/crop-root interactions; this was a stratified random sampling around the tree and nominal tree (in control plot) positions. Since the results for these biomass samples are presented (section 8.3) as plot means at different sampling depths, the details of the stratification are therefore not described. Four cores were taken from each of plots 372 and 346 (both with trees) and 348 (no trees).

The soil coring apparatus is shown in plate 8.2 and comprises of a petrol-driven percussion hammer ("Cobra", Atlas Copco Ltd., Sweden) and a coring tube (Model 08.18 Eijkelkamp, Giesbeek, Netherlands) containing a series of HDPE plastic sample tubes. The inner tubes divide the core into five sections (0-10; 10-20; 20-40; 40-60 and 60-100 cm depth). The samples collected were washed free of soil using a root-washing apparatus (Root-washer, Delta-T Devices Ltd., Cambridge) and oven dried (70° C) without further separation.

8.2.6 Aeolian material

The Harmattan wind with its associated dust storms are a major meteorological feature of the North East Nigeria region (see section 1.7). It is acknowledged that this material will play an important rôle in pedological processes.

Small quantities of sand and other solid particulates carried on the wind throughout the year have been collected in a series of sand traps located around the New Marte field site. Three of these traps were situated close to plots 338, 340, 348, 362, 364 and 372 (see Figure 5.1) used for the other soils analysis and the organic matter and nutrient sampling. With the small quantity of sample material available (total of all samples: 2-3 g), it was decided to examine the physical characteristics and mineralogy, rather than the nutrient chemistry, of this material and these results are reported in section 3.5.

8.3 RESULTS

8.3.1 Litter-fall measurements

The mean values for litter collected during the 1993 growing season in samplers directly under trees (≤ 2.25 m from tree stem) and in positions away from trees (> 2.25 m away from tree stem) (but still in "tree" rather than "control no tree", plots - see figures 5.2-5.9) are presented in table 8.1. The standard error of the differences between the mean values is also shown.

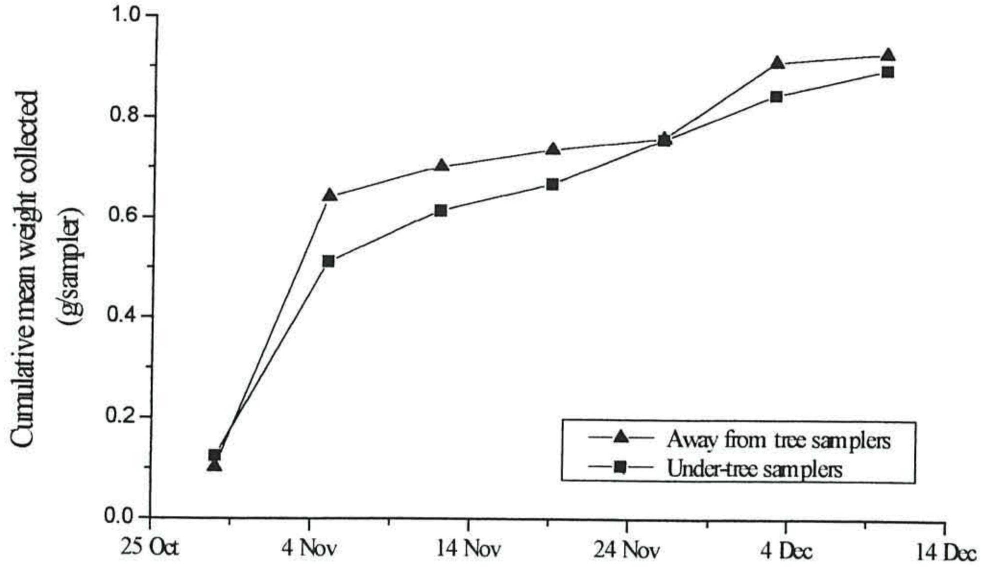
Table 8.1 - Mean weights of litter collected.

Date sampled	29.10.93	5.11.93	12.11.93	19.11.93	26.11.93	3.12.93	10.12.93	Total
Mean weight (g) - under tree collectors	0.126	0.386	0.102	0.053	0.089	0.088	0.050	0.894
sd	0.202	0.411	0.162	0.114	0.176	0.139	0.114	
n	30	28	27	27	29	28	30	
Mean weight (g) - away from tree collectors	0.103	0.539	0.059	0.035	0.023	0.151	0.017	0.927
sd	0.288	0.733	0.140	0.064	0.064	0.468	0.057	
n	15	15	15	15	15	15	15	
sed	0.035	0.075	0.030	0.021	0.031	0.025	0.020	
P <0.05	ns	*	ns	ns	*	*	ns	

Since each sampler collects over an area of 706 cm^2, the mean total quantities of 0.894 g and 0.927 g, for the under-tree and away-from-tree samplers respectively, represent litterfalls of 12.7 g/m^2 and 13.1 g/m^2 over the seven week period sampled. To illustrate the trend in cumulative litter-fall measurements for the period October - December 1993, figure 8.3 shows the time series of mean value measurements.

Using the difference between the "fresh" and "oven-dry" biomass weights of the 18 batches of *Acacia nilotica* tree leaf samples plucked from the trees in January 1995, the mean moisture content of these samples can be calculated. For all three trees sampled, the mean moisture content was 8.28 %. This moisture content value helps characterise the tree leaf material for a better estimate of the chemical inputs of litter-fall, when used in the SCUAF model, since Russell (1973) notes that the N content of the dry matter of plant material is normally <0.5 % when the moisture content of the material <10 %.

Figure 8.3 Cumulative Litterfall - 1993 growing season
Mean values from litter collectors in tree plots



8.3.2 Rainfall

The results of the chemical analysis of the rainfall samples are presented in figure 8.4. This figure shows the relationship between the date of the rainfall event in the 1993/4 rainy season and the quantity of each element or ionic species measured for each of these rainfall events. Each datum represents the rainfall for a single day, with samples only taken after a rainfall event. All elements/ionic species are plotted in figure 8.4 on a $\log_{10}$ scale since there were found to be a small number of large values relative to the mean values and plotting on a logarithmic scale enables a clearer comparison. As a summary of the whole season, table 8.2 contains the mean values, range and standard deviation of the rainfall chemistry analyses.

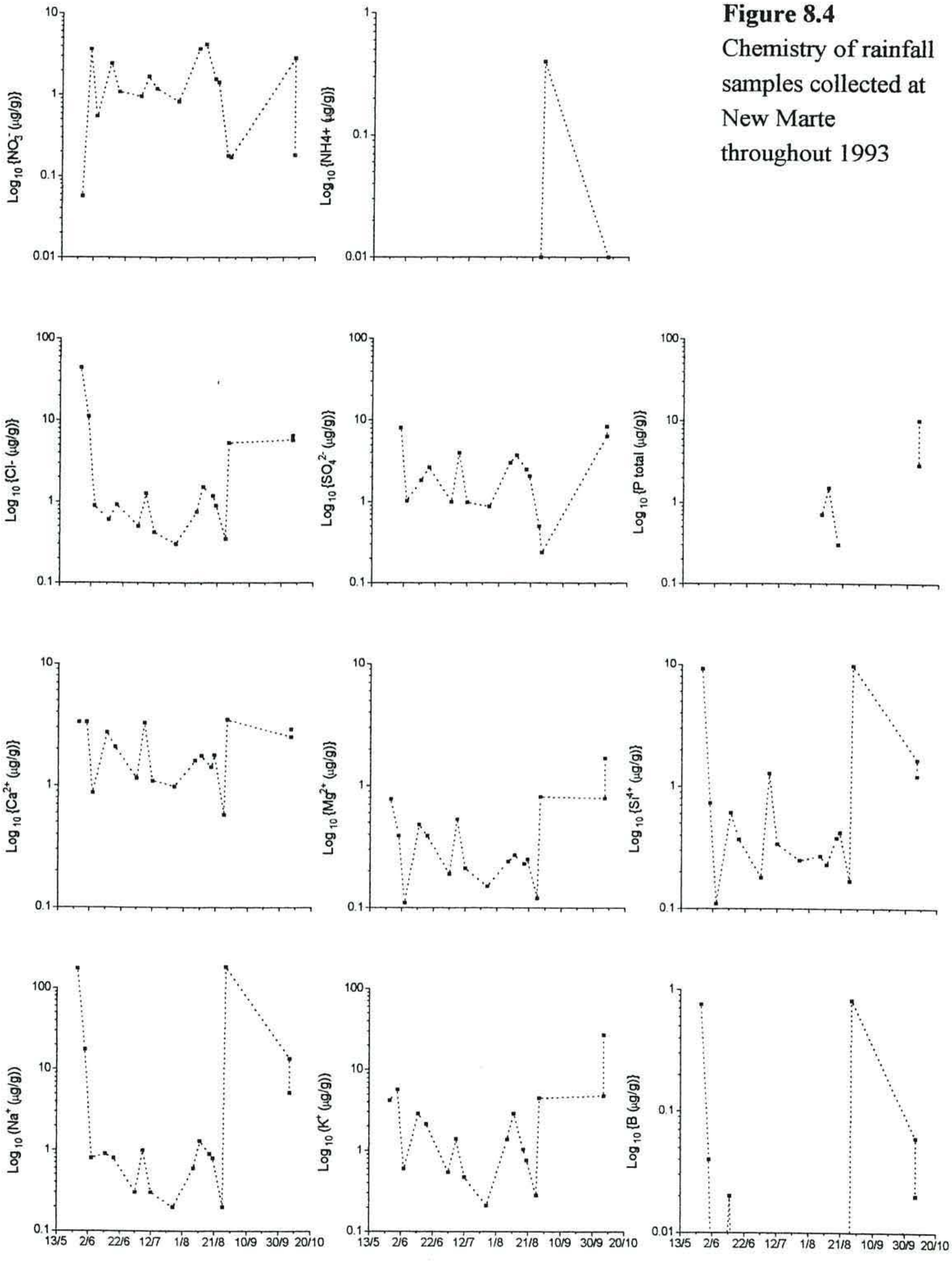


Figure 8.4
Chemistry of rainfall samples collected at New Marte throughout 1993

Table 8.2 Chemical analysis of water samples

	Date	Position		Na	K	Ca	Mg	B	SO4 - -	tot. P	Si	Cl -	NO3 -	NH4+
				Element / ionic species (ppm)										
Rainfall	all year	weather	mean	**23.67**	**3.57**	**2.05**	**0.45**	**0.10**	**2.77**	**0.92**	**1.60**	**4.84**	**1.56**	**0.02**
		station	sd	58.70	6.29	0.98	0.39	0.26	2.61	2.51	2.99	10.53	1.33	0.10
		n=17	max	184.00	27.00	3.49	1.68	0.81	8.33	10.20	9.71	44.00	4.20	0.40
			min	0.20	0.21	0.58	0.11	<	<	<	0.11	0.30	0.06	<
Throughfall	October sampling	Tree plots	mean	**3.07**	**15.11**	**11.39**	**1.93**	**0.06**	**5.66**	**0.44**	**0.88**	**6.37**	**0.77**	<
			sd	3.85	15.95	14.88	1.86	0.13	6.46	0.55	0.82	7.01	1.08	<
		n=67	max	32.00	85.60	100.80	11.80	0.92	49.00	3.50	5.60	49.50	4.13	<
			min	1.20	1.54	1.53	0.34	<	2.02	<	0.17	1.50	0.01	<
		Control	mean	**2.19**	**4.11**	**2.69**	**0.71**	**0.01**	**3.63**	**1.08**	**0.46**	**2.27**	**1.41**	**0.05**
			sd	0.62	3.70	1.13	0.48	0.01	1.54	1.76	0.29	1.40	1.22	0.21
		n=19	max	3.90	17.60	6.28	2.16	0.02	8.52	7.70	1.43	6.95	4.95	0.92
			min	1.40	1.38	1.66	0.32	<	2.15	<	0.17	1.08	0.08	<
	July sampling	Tree plots	mean	**0.61**	**1.20**	**1.34**	**0.29**	**0.73**	**1.17**	**0.04**	**0.50**	**0.54**	**0.44**	<
			sd	0.33	0.50	0.28	0.08	1.76	0.25	0.12	0.34	0.21	0.20	<
		n=70	max	2.10	2.68	2.24	0.49	5.06	1.97	0.50	1.62	1.17	1.67	<
			min	0.20	0.48	0.91	0.15	<	0.84	<	0.11	0.18	0.29	<
		Control	mean	**0.63**	**0.94**	**1.30**	**0.26**	**0.03**	**1.13**	**0.02**	**0.35**	**0.52**	**0.35**	**0.01**
			sd	0.31	0.23	0.25	0.07	0.11	0.21	0.10	0.14	0.29	0.08	0.05
		n=57	max	1.60	1.51	2.15	0.44	0.38	2.00	0.70	0.78	1.55	0.79	0.35
			min	0.20	0.47	0.86	0.11	<	0.77	<	0.13	0.20	0.03	<
Analysis of mean values				Standard error of differences between means (sed)										
	July	tree vs. control plots		0.06	0.07	0.05	0.01	0.23	0.04	0.02	0.05	0.04	0.03	0.01
			P<0.05	ns	*	ns	*	*	ns	ns	*	ns	*	ns
	October	tree vs. control plots		0.89	3.70	3.43	0.43	0.03	1.50	0.25	0.19	1.62	0.29	0.03
			P<0.05	ns	*	*	*	ns	ns	*	*	*	*	ns
	Tree plots	July vs. October		0.46	1.91	1.78	0.22	0.22	0.77	0.07	0.11	0.84	0.13	0.00
			P<0.05	*	*	*	*	*	*	*	*	*	*	ns
	Control plots	July vs. October		0.11	0.49	0.16	0.06	0.02	0.21	0.23	0.05	0.19	0.16	0.03
			P<0.05	*	*	*	*	ns	*	*	ns	*	*	ns

8.3.3 Throughfall

Table 8.2 also contains the mean values, ranges and standard deviations of the throughfall chemistry analyses, in addition to the rainfall analyses. For these throughfall measurements, the table includes standard errors of the differences between means (sed) for each element/ionic species both between tree plots and control plots for the same rainfall event and between the two different rainfall events for both the tree plots and control plots. Significant ($P<0.05$) differences are also indicated.

The spatial distribution of two major ionic species (Ca^{2+}, Cl^-) and a macro-nutrient analysed (NO_3^-) are shown mapped in figures 8.5 - 8.7 for the first sampling time. These figures are interpolated maps, produced using the same procedures as the other plot-level soils measurements (Chapter 5). Like the litterfall measurements, the sampling in the tree plots was stratified, with a bias towards near-tree locations, so these maps are not strictly comparable with the soil measurements (Figures 5.18-5.31). However, the large number (160) of throughfall sample collectors would suggest that this mapping is a reasonably even representation of the throughfall distribution.

Figure 8.5 Throughfall chemistry - Ca^{2+}

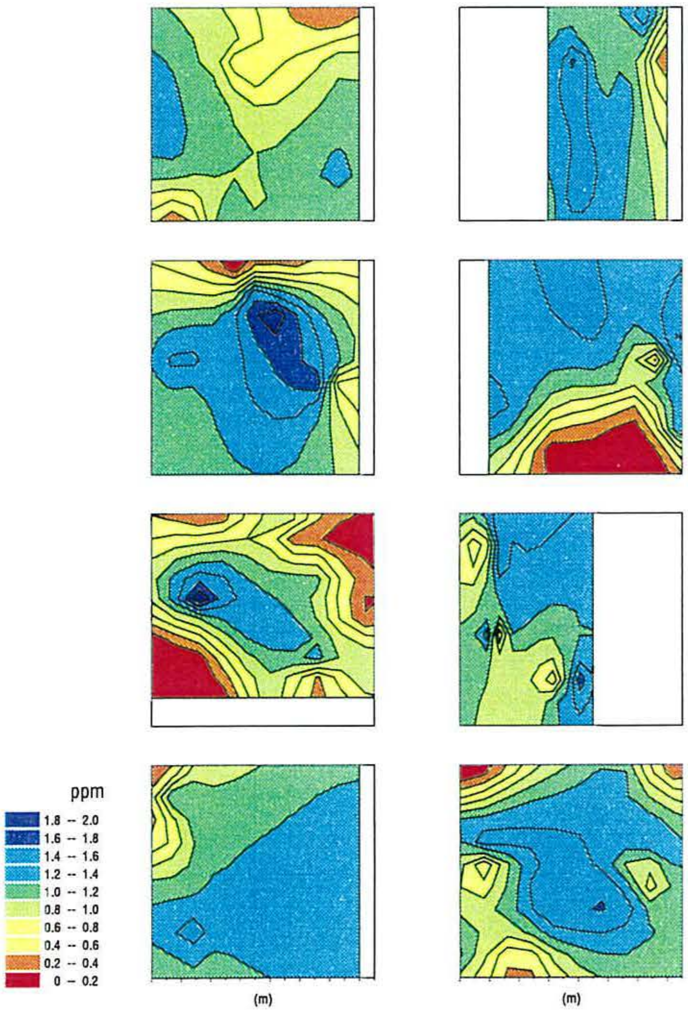


Figure 8.6 Throughfall chemistry - Cl^{-}

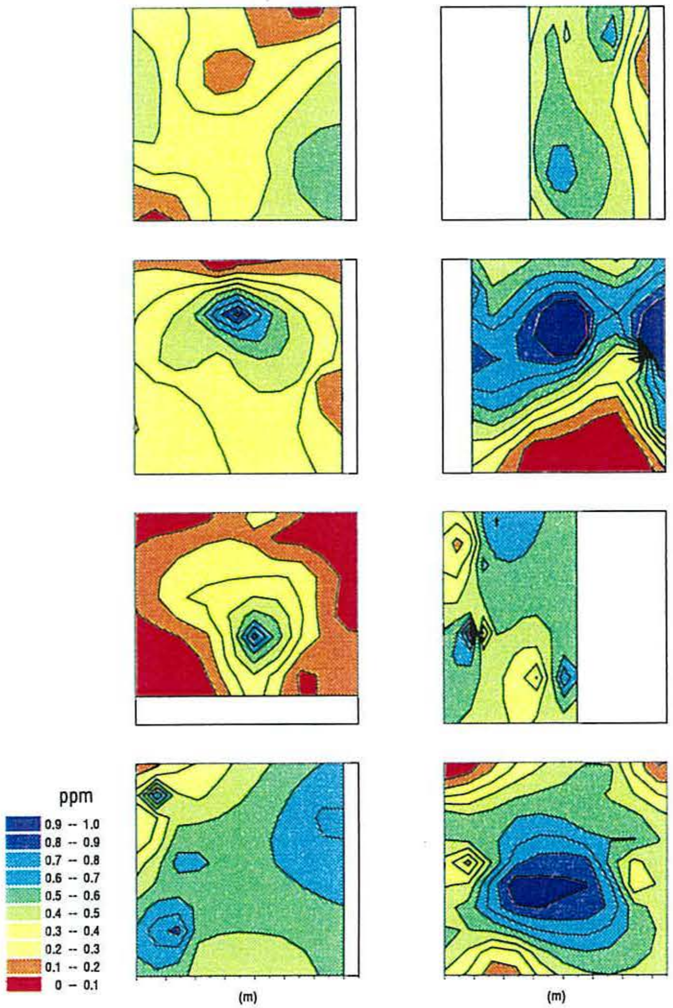


Figure 8.7 Throughfall chemistry - NO_3^-

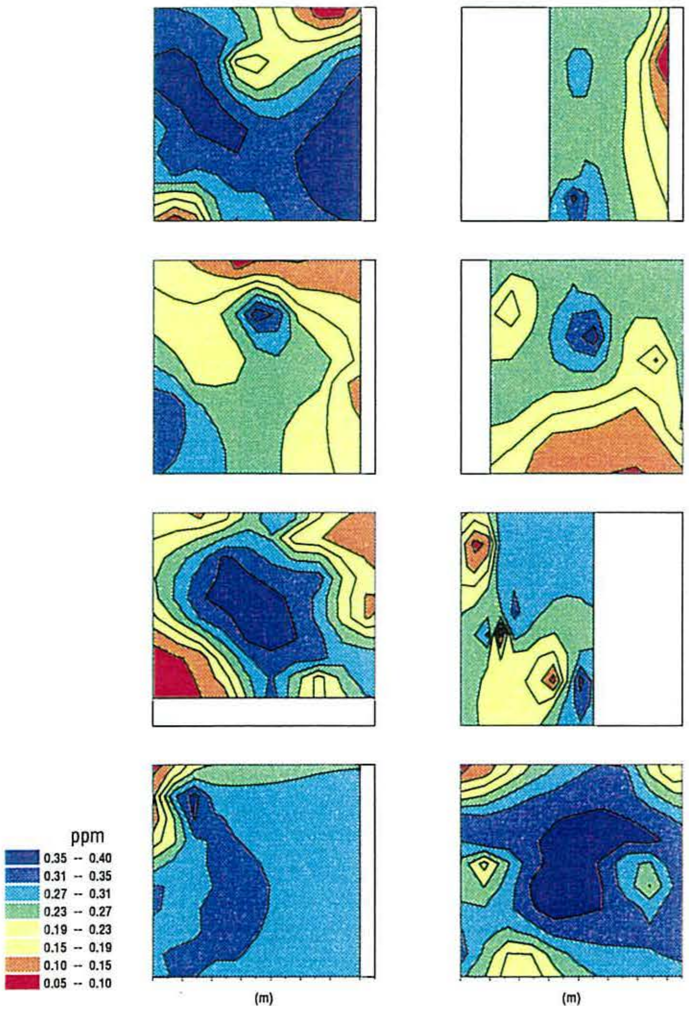
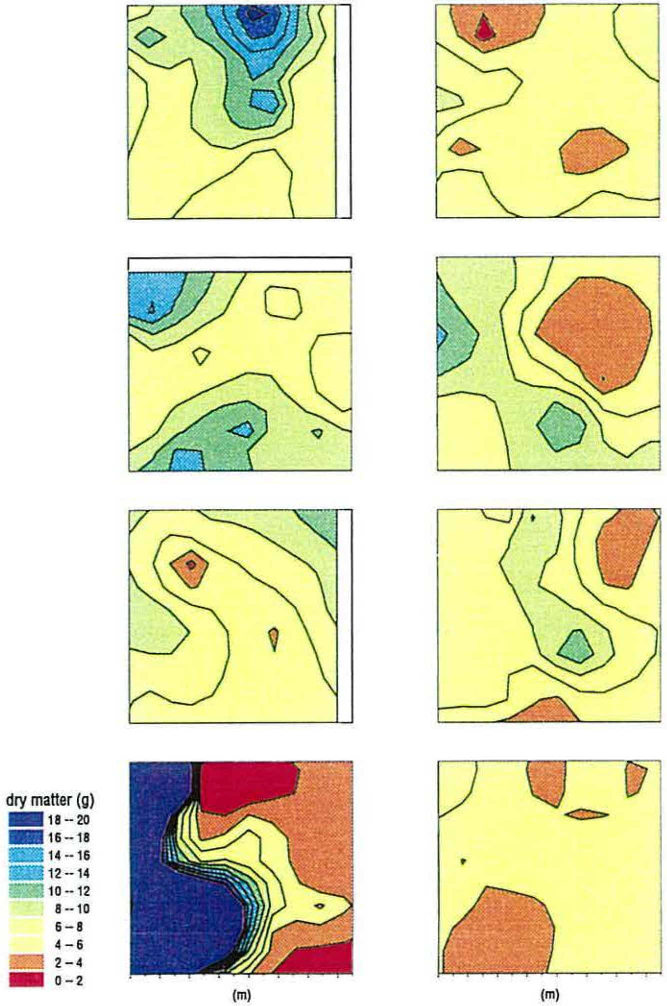


Figure 8.8 Standing dead material



8.3.4 Standing dead material

The standing dead material sampled from directly above each of the soil sampling positions has been mapped (Figure 8.8). This is in the same style and with the same spatial distribution as the soil sample measurements (Chapter 5).

8.3.5 Biomass decay and herbaceous regrowth measurements

The values of both the above- and below-ground biomass measurements are presented in table 8.3, with each datum representing the mean of the measurements made at each time interval (September 93, January 1994, July/August 1994) across all eight plots.

Table 8.3 Biomass decay/regrowth measurements

	above-ground			below-ground
	weight Sept. 93 g	weight Jan. 94 g	weight Aug. 94 g	weight Sept. 93 g/dm^3
mean	142.1	98.7	298.6	1.17
sd	114.1	84.8	168.6	0.61
max.	503.2	259.0	635.0	2.78
min.	6.8	10.0	37.0	0.43
n	72	15	15	32

8.3.6 Below-ground stratigraphy of sorghum and tree root biomass

The results of the stratigraphic sampling of root material for biomass estimations are shown in Table 8.4, where the root distribution down-profile is compared between sampling locations close to trees (<1.25 m) and positions away from trees (>2.5 m). Despite the sampling being stratified with a bias towards close-to-tree measurements, in this instance the mean values are calculated from measurements on the same number (8) of samples.

Table 8.4 Stratigraphic sampling of the below-ground (root) biomass

Sample depth	weight / unit volume (g/dm^3) Positions away from trees		Positions close to trees			
	mean	sd	mean	sd	sed	P<0.05
0-10 cm	1.979	0.656	3.423	1.636	0.623	*
10-20 cm	1.119	0.972	1.185	1.250	0.560	ns
20-40 cm	0.515	0.538	0.348	0.190	0.202	ns
40-60 cm	0.216	0.149	0.197	0.136	0.071	ns
60-100 cm	0.184	0.127	0.101	0.036	0.047	ns
total	4.015		5.255			

8.4 DISCUSSION OF RESULTS

8.4.1 Above-ground nutrient inputs

The periodic litterfall measurements (Table 8.1) reveal that only small quantities (<5 g/sample location/period) are lost and fall beneath the trees during the growing season. The relatively large increase in litterfall between the first and second sampling period (figure 8.3) is possibly due to the onset of drier conditions (*cf.* figure 1.7). It is likely that greater litterfall occurs in more windy conditions, particularly when the Harmattan wind, which carries large quantities of particulate material, abrades the dried-up tree leaves. For the sake of comparison with other reports, if the measurements over the period in which the litterfall is collected is extrapolated from 7 weeks to 20 weeks (the approximate length of the growing season), then the total quantity of litter collected represents 37 g/m^2/growing season. This quantity is comparable with the range of quantities reported (10-50 g/m^2/year) by Rodin and Bazilevich (1967 - restated by Collinson, 1977) for litter samples taken from a wide selection of *Acacia* species found across semi-arid and savanna areas. This result also conforms to the average primary productivity of dry matter (range 10-250 g/m^2/year; mean 90 g/m^2/year) found for this kind of semi-arid environment (Jordan, 1985).

There is no evidence for the influence of tree on the quantities of litter collected at sampling positions <1.25 m and >2.5 m from the tree. This suggests that a reasonably even spatial distribution of tree litter occurs in tree plots. If this is the case then nutrient accumulation under trees, which has been often reported in semi-arid and arid areas (*e.g.* Virginia, 1986), must be due to other factors such as root turnover, stemflow and throughfall.

For tree planting in semi-arid regions, the chemical inputs to the soil from the leaf litter have received little attention in previous studies, which have mainly tended towards humid tropical systems (*e.g.* Jordan, 1985). Prior *et al.*, (1987) considered a number of tree species in terms of N metabolism and analysed dried tree leaves. Amongst their findings were high (> 2000 μmol/g) values for tannin (*i.e.* mostly polyphenolic) compounds in *Acacia nilotica* leaves; these values were higher than for any other tree species considered, including six other *Acacia* species. There is a suggestion that the rôle of these tannin compounds may be to prevent the collapse of cell walls during periods of water stress to the plant. Prior *et al.*'s study also found that relatively large quantities of N-containing compounds (4-hydroxyproline, and quaternary ammonium compounds) are accumulated in *A. nilotica* leaves as a result of the trees' response to drought conditions. Since these compounds will form a large part of the total N contained in the tree leaf, which in turn will be returned to the soil as litter, this suggests that year-on-year changes in rainfall (Figure 1.6) will affect the quantity of N reaching the soil from tree litter (Table 8.2).

Whilst any spatial variation in the influence of the trees in terms of tree litter may not be particularly pronounced, a comparison of the chemistry of the rainfall and throughfall (Table 8.2) suggests that there is a distinct effect of the trees in terms of the chemistry of the water reaching the soil. This would be expected to have implications for the soil structure as well as for the chemistry of the soil. The high tannin content of the tree may also affect the soil structural stability, with polyphenolic compounds inhibiting growth of other flora thus reducing the organic matter content of the soil and reducing aggregative processes.

The rainfall chemistry throughout the year is erratic for several elements, with NH_4^+, Total P, Si and B showing "spikes" in their distribution, from levels below detection to single isolated peak values. Despite the results being the mean of three samples taken after each date (event), these may be due to sample contamination by bird faeces (NH_4^+) or aeolian particulates (Si). For the other elements/ionic species, there is little evidence of trends or clusters of results throughout the rainy season. The effect of trees on the throughfall chemistry, however, does appear to vary throughout the rainy season, with slightly more elements/ionic species showing differences between tree-influenced and control (no-tree) in October than in July (Table 8.2). The elements and ionic species with significant ($P<0.05$) differences between the tree-influenced and control measurements throughout the year are K^+ and Mg^{2+}, but the most pronounced differences are seen with SO_4^{2-}, Cl^-, Na^+, K^+, Ca^{2+} and Mg^{2+} in comparison of the tree samples in the October sampling period to the corresponding control samples and to all of the samples (both tree and control) taken in the July sampling.

Whilst the table of mean values (Table 8.2) for the throughfall measurements shows significant differences between the samples taken from the control plots and those from tree plots, this is not as apparent in the spatial distributions (Figures 8.5 - 8.7) of the three ionic species (Ca^{2+}, Cl^-, NO_3^-) which reveal no distinct trend with respect to positioning of the collectors under the tree canopies. Similarly the quantity of the standing dead material above the soil sampling positions appears to have no relationship with the presence or absence of trees in the plot. However it has been seen (section 5.5.1) that the plant species found will vary depending on, amongst other factors, the texture of the soil.

The standing dead plant material sampled in June 1993 (Figure 8.8), represents the material that has been resistant to degradation by physical or biotic means throughout the dry season. It could be envisaged that this material provides the soil with some protection from wind erosion during this period and from water erosion during the initial rains.

The large quantities of plant biomass (table 8.3) found in the form of weeds at the start of the crop growing season in late-August/September (*i.e.* immediately after transplanting) suggests that, with early weeding, a large quantity of material is subject to losses for a relatively long period. The subsequent decay of this material (January) and the seemingly enhanced regrowth of other plant material (August) further suggests that a fallow period with synchronised inputs of organic material by weeding may improve the subsequent growth of plants including crop plants, but in this case illustrated by weed regrowth. This effect could be due to a number of factors, including the effect of meso-fauna on the degradation of weeded material.

8.4.2 Below-ground nutrient inputs

In agrosilvicultural systems such as the experiment at New Marte, an important factor in the below-ground interactions is the possible competition between the roots of the tree and those of the crop plants for the available soil nutrients (Young, 1989). It is unlikely that the crop roots will extend below 40 cm and will, with the fine tree roots, be concentrated in the upper 0-10 and 10-20 cm layers. The *Acacia spp.* in common with other semi-arid zone tree species possess a deep tap root which may extend to tens of metres depth (Hutchinson and Dalziel, 1954). In this instance the roots have not been separated into the two (tree and crop) components but are a bulk mixed sample. In both the samples close to, and distant from, the trees the largest root biomass is found in the two samples closest to the surface (0-10 cm and 10-20 cm depth). This suggests that the greatest root competition between tree and crop roots is likely to be in these upper layers. The results show a significant ($P<0.05$) difference between the mean values of the root biomass found in the upper (0-10 cm) layer between samples taken from close to trees and from those further away from them. It is therefore likely that the trees are competing with the crop in this upper layer for water and nutrients. Whilst other studies at New Marte have examined crop and tree root competition throughout the growing season, the functionality of the tree roots has not been investigated (unpublished ODA Project R4850 - final report, 1996). It is possible therefore, that the primary function of the tree roots in this upper layer is to gain water rather than nutrients for the tree, which would fit the so-called "soil-mining" view of agroforestry tree planting where trees utilize nutrients, especially P, from greater depths than crop plants and these nutrients, through root turnover and litterfall, are returned to the soil and are then potentially available for crop use.

8.4.3 Individual nutrients

In semi-arid areas, the macronutrient **phosphorus** is often considered to be the most limiting factor to plant growth after the availability of water. In semi-arid and other tropical regions a large part of the plant-available P will be in the organic material of the surface soil (Russell, 1973), and consequently susceptible to being lost by surface erosion processes. Lately, it has become recognised (Giller and Wilson, 1991) that "green manuring" of tropical soils with leaf material can be used to suppress some of the irreversible adsorption of P by the soil matrix *i.e.* the input of C and N can also maintain the plant-available P. A small amount (mean values ≤1 ppm) of P is found in the rainfall and throughfall samples but no pattern of deposition emerges, since the ranges of these measurements is large and the rainfall measurements show no trends throughout the rainy season. However, the quantity of P in the October throughfall measurements is significantly higher than the July measurements. This indicates that the tree leaves are being leached of greater quantities of P late in the rainy season, either as a result of less frequent rain, or due to differences in the quantity, morphology and chemistry of the tree leaves.

Lindley and Deans (1992) found, as expected, the highest concentrations of P in the above-ground biomass of *Acacia senegal* in the tree's fruit and in the leaves. As would be similarly expected, with increasing age these trees contained greater quantities of P in the woodier material. If P is found to be limiting to the crop component in a silvi-arable agroforestry system and the trees are seen to be "mining" the soil for P, then these results emphasise the importance of the timing of pruning or removal of the trees.

The input of **nitrogen** to the soil from throughfall, despite showing significant differences between the tree and control plots, is likely to be small, as will be the rainfall contribution, compared to inputs from the decay of above- and below-ground plant material. N fixation by the leguminous trees may also be a major source of N, but since this factor has not been quantified in this study, the SCUAF modelling (section 8.5) has used assumed rates of both symbiotic and non-symbiotic N fixation in order to produce a C and N budget. Issues relating to N fixation in agroforestry systems have been discussed by Giller and Wilson (1991) and they point to specific areas where such systems can be improved including selection of rhizobial strains and improved inoculation. In the conditions experienced at New Marte, in particular the prolonged period of flooding and the long dry season, the trees may be required to transport oxygen from shoot to root during periods when the soil is waterlogged, in the manner suggested by Giller and Wilson (1991), in order for the rhizobia to survive.

Of the other elements considered in the throughfall and rainfall analyses, the most distinct changes are seen in the **chloride** and **calcium** contents of the throughfall (table 8.2), where larger quantities were found in the October sampling, compared to the July sampling. These increases do not match any trend in the rainfall analysis, and must therefore be related to the influence of the trees, presumably from leaf exudation. Whilst leguminous plant species are particularly sensitive to deficiencies in **potassium** (Collinson, 1977), at New Marte the supply of K and **magnesium**, two macro-nutrients, should not be limiting since they are associated with the presence of smectitic clay minerals. The slightly alkaline nature of the soils at New Marte (Chapter 4) may make them susceptible to **iron** deficiencies if iron is precipitated as insoluble hydroxides. This would become more apparent if pH values rose as a result of salinization; this is a process which may occur in neighbouring areas as a result of the irrigation of these soils with water obtained from Lake Chad as described by Adams (1992). Salinization has also long been associated with **boron** toxicities (Richards, 1954), since the B is not leached out of the soil to the same extent found in acid soils. The 0.1ppm mean concentration of B in the rainfall samples is relatively low, however, suggesting that any B toxicity found in the New Marte and neighbouring irrigated soils would be inherited from soil parent materials rather than influenced by rainfall.

The inputs of various macro- and micro- nutrients to the New Marte soils have been considered in this section. The following section concentrates on modelling the processes involved in the cycles of two macro nutrients: C and N.

8.5 MODELLING OF AGROFORESTRY SYSTEMS: AN EXAMPLE USING "SCUAF" WITH DATA FROM NEW MARTE

8.5.1 Introduction

In common with many agronomic and forestry experiments in the tropics, the results of soil measurements obtained at New Marte are being analysed after relatively short periods of experimental treatment, which in this instance is the tree-planting. The use of modelling allows predictions of longer-term (10 + years) effects on the soil to be made. Numerous models have been proposed to gain better understanding of land-use systems and, more recently, agroforestry systems. Many of these models have been developed for a particular subject of interest. Examples include: organic matter turnover in soils (CENTURY - Parton *et al.*, 1987), soil erosion by water (USLE - Wischmeier and Smith, 1960; PERFECT - Littleboy *et al.*, 1989), and combinations of these two soil factors (SCUAF - Young and Muraya, 1990). The last of these models, (SCUAF - Soil Changes under Agroforestry), was specifically developed to model agroforestry systems, particularly agro-silvicultural systems. It encompasses soil erosion and turnover of C and N, based respectively on the FAO form of the universal soil loss equation (USLE) (FAO, 1979) and on Nye and Greenland's (1960) nutrient cycling studies (Young and Muraya, 1990).

8.5.2 Use of the "SCUAF" Model

The SCUAF model is designed for predicting changes in soil nutrients (C, N) over periods of several years or more, rather than on short day-to-day terms, where the modelling of soil-water interactions is more commonly attempted. In order to make predictions of future soil changes for a particular defined agroforestry experiment, the SCUAF model requires inputs of data of several types. These data can be classified into environmental site factors (*i.e.* slope of site, climate, soil characteristics, site drainage) and specific nutrient/biomass factors (*i.e.* initial soil C and N chemistry, addition/removal of organic materials).

Figures 8.9 and 8.10 (taken from Young and Muraya, 1990) respectively show the C and N cycles used in the SCUAF model. These "schematics" show the "pools" and "fluxes" (or in alternative modelling terminology the "compartments" and "flows") covered by SCUAF. The growth rates for the tree and plant materials are supplied to the model rather than calculated as in other models (*e.g.* CENTURY), but most other plant-related parameters are calculated.

Since no chemical analysis of the plant material sampled at New Marte was undertaken, several of the standard default values of SCUAF have been used for the chemical composition of the litterfall, and below-ground root-turnover organic inputs. These default values are pooled from a number of cited literature sources, including many that are also used by Parton *et al.*, (1987). They are used in the SCUAF inputs shown in appendix 5 unless other sources are considered more appropriate for the conditions at New Marte; these sources are highlighted in appendix 5.

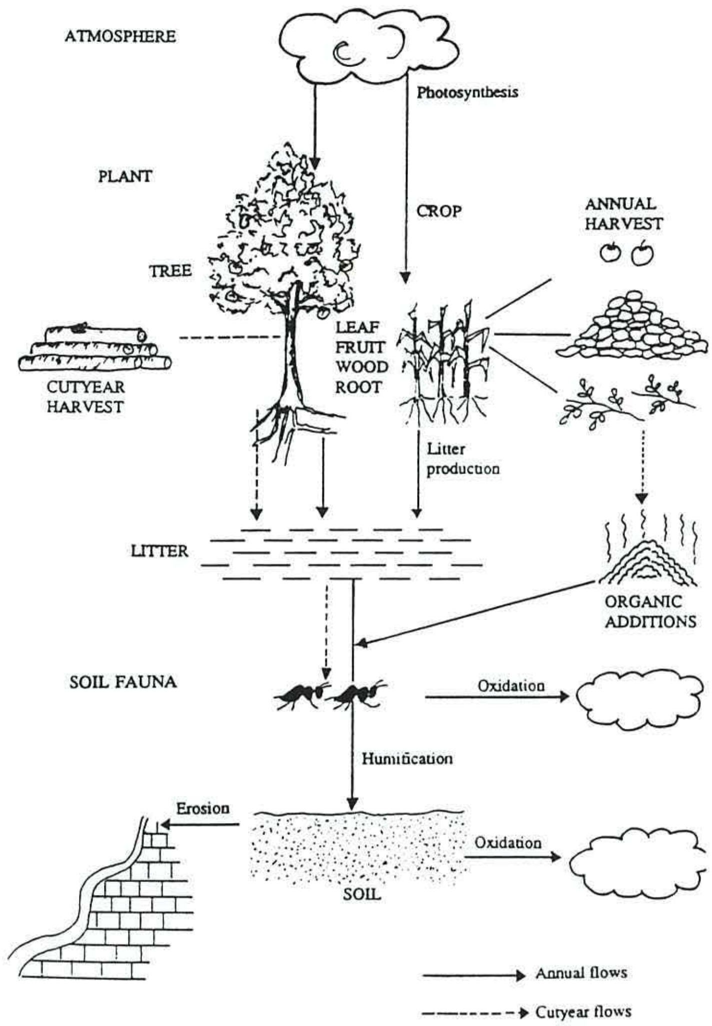
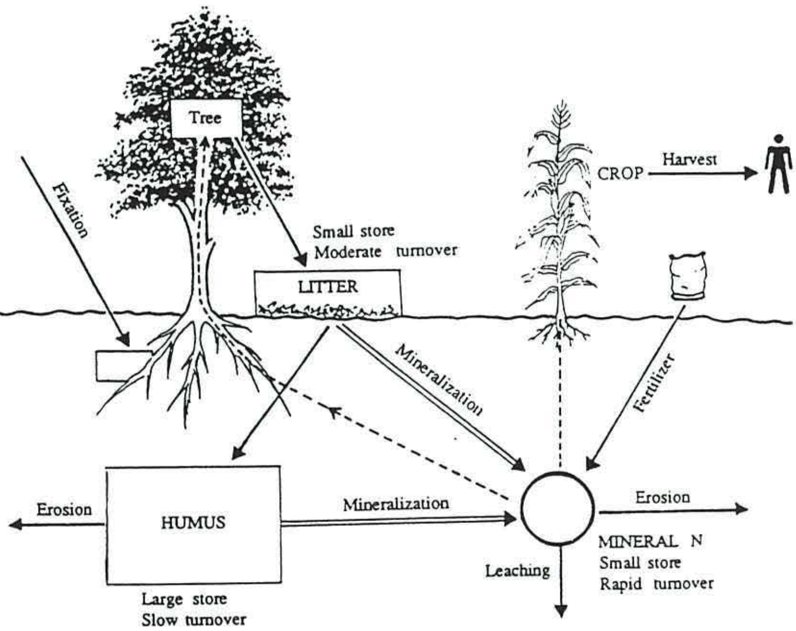


Figure 8.9 Carbon cycle used in SCUAF model
Figure 8.10 Nitrogen cycle used in SCUAF model
(both figures from Young and Muraya, 1990)



8.5.3 SCUAF simulation model of New Marte agroforestry experiment

The SCUAF model requires a mixture of basic "file-handling" inputs and inputs relating to the experiment being simulated. Both of these sets of inputs are reproduced here in order that the model may be reused and appended with any new data sets generated from New Marte in possible future experimentation. The model simulated assumes that there is no harvesting of tree materials, and that a crop is grown under the tree canopy, *i.e.* that there is more than 100 % coverage by the tree and crop combined. Another assumption made is that the land coverage of the trees increases through years 1-10 as they grow and in so doing the area in which sorghum is grown diminishes until no sorghum is grown in years 10-15. Further it is assumed that the above-ground growth of the crop is removed each year and that no long-term stable humus material is retained in the soil. These assumptions have been made in order that the model may best illustrate the intercropped plots used in the detailed plot experimentation (see figure 5.1).

8.5.4 Results of SCUAF simulation model of New Marte data

The results of the SCUAF simulation with the conditions tabulated in Appendix 5 are presented in figure 8.11 as a series of graphs of the variables *vs.* time. A fifteen year period has been used in the model simulation since it would be expected that within this period the influence of trees on the soil may become obvious. The SCUAF model makes predictions of the changes in plant growth and quantities of tree and crop harvested. It is acknowledged by the authors of SCUAF that such predictions are as a result of soil changes, and many other factors (in this example at New Marte, climatic) are responsible for the yields obtained. These outputs of the model are omitted from figure 8.11 since they are of less interest than the predictions on soil chemistry.

8.5.5 Discussion of SCUAF outputs for New Marte simulation

The principal use of models such as SCUAF in agroforestry are that they predict changes in a property over longer periods than can be considered in many field experiments (Anderson *et al.*, 1993). This allows objective comparisons between different experiments to be made using a series of assumptions, which themselves may differ over time as more information on agroforestry interactions becomes available in the scientific literature. In this instance, since there is no desire to make an objective comparison with another system at a different location away from New Marte using SCUAF, trends in chemistry and biomass are considered rather than the absolute values determined by the model's calculations. Here, the model is specifically considered in terms of changes to the soil's nutrient status rather than in changes in the plant compartments of the C and N cycles or in potential crop and tree yields.

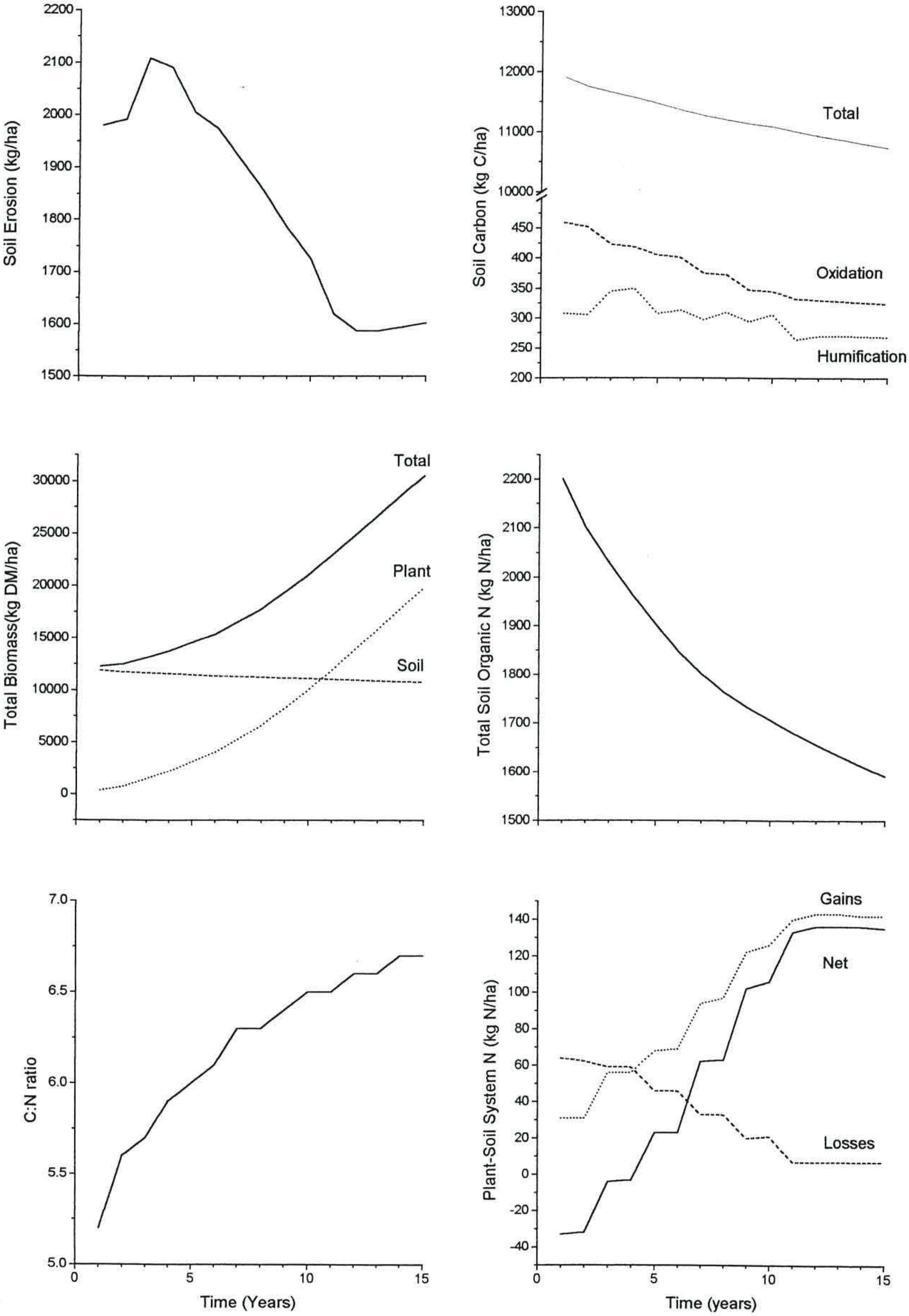
The outputs from SCUAF shown in figure 8.11 reveal several expected trends. Firstly, as the plant biomass increases, the total soil organic N and total soil C decrease by similar quantities, this would be expected and helps confirm that the model is robust. More interestingly, the soil erosion calculation, which is a function of various site factors, environmental variables and the influence of plant growth, shows a marked increase in the third year of the simulation, before falling as the trees become more established, and finally levelling off. This is an example of the contrast between years 1-10 when an intercropping system is adopted in the model definition, and in years 11-15 when a tree monocrop is defined. Similarly the "plant-soil system N" is predicted to stop increasing with the cessation of the sorghum cropping, with total gains (N fixation) and losses (harvesting of crop, erosion losses, leaching, gaseous losses) remaining at near constant levels.

The soil's C:N ratio is shown to steadily rise throughout the period modelled but the rate of increase diminishes with the switch from agroforestry intercropping to a monoculture. The increase in the plant-soil N is associated with the N symbiotically fixed by the *Acacia nilotica* trees. In the field sampling of soil profiles (Chapter 2), no nodules on tree roots were found, but it has been found for many leguminous trees planted in semi-arid areas that nodulation and N fixation occurs only at depth (*i.e.* closer to the permanent water table; Giller and Wilson, 1991). If N fixation is occurring at depth (>1 m) rather than close to the surface, then the net N available to the soil in the crop rooting zone (0-40 cm) as a result of tree inputs may be smaller than that estimated by the SCUAF modelling in this 0-40 cm zone.

The yearly basis of the SCUAF model, whilst suited to long-term modelling, is not well suited to considerations of synchronised applications of inputs in the way which is envisaged, for example, in the TSBF experimental programme (Anderson and Ingram, 1993). Anderson *et al.*, (1992), in their review of agroforestry modelling, also comment on the relative simplicity of the SCUAF model, with the implication that it may be further improved by incorporating a greater number of sub-structures - a process termed by modellers as "disaggregation", *i.e.* consideration of more than one soil horizon and/or resolution of the tree component to the level of an individual tree. Whilst the ability to resolve information at more than one spatial level may be seen to be desirable, the quantitative data requirements would be much greater and the resulting simulations may subsequently be weakened by too many assumptions being made.

The specification in the SCUAF model of the C and N cycles has included all the terms considered of major importance in discussions of nutrient turnover in humid tropical conditions. The applicability of the SCUAF model to the conditions at New Marte could be challenged since New Marte has an unusual climate, and therefore cropping, in that the sorghum is transplanted and then grown on residual moisture after the major rainfall events of the rainy season. It could be envisaged that this feature of the cropping will possibly produce a distinct increase in the amount of dried-up above-ground plant material reaching the soil during the arid period immediately post-harvest, when both tree leaves and crop residues reach the soil, with some nutrients then lost (*e.g.* volatilization of N) during the dry season. Such implied criticism of the SCUAF model must be balanced with the relative simplicity of the model. Also even greater demands for quantitative data over shorter temporal periods would be required for an extended model where the synchronicity of the planting and the nutrient inputs from litter and other biomass turnover are considered important.

Figure 8.11 SCUAF model outputs (variable *vs.* time)



8.6 SUMMARY AND CONCLUSIONS

Many previous authors have considered the removal of trees from the semi-arid landscape and the effects that this and subsequent continued cultivation, is having upon nutrient cycles and upon water holding capacity, (Gerakis and Tsangariakis, 1970) and in particular on nitrogen cycling (Bernhard-Reversat and Poupon, 1980). Efforts to avoid the depletion of soil organic matter in tropical cropping systems has led to the attempts to model agroforestry systems, since these systems potentially offer the greatest complimentarity between the components utilizing soil resources (Young, 1989).

Apart from influencing directly the throughfall and stemflow chemistry and contributing organic materials to the soil, the trees will also have an effect on nutrient inputs through secondary and somewhat indirect mechanisms. Trees at New Marte were seen to influence the populations of various macrofauna, such as the granivorous weaver birds (*Quelea quelea*) which are often found in large populations and may redistribute considerable quantities of P in their faeces.

From the data available for the plots sampled, broad conclusions on the spatial distribution of organic and nutrient inputs to the soil can be made. The litterfall seems to show no stratification relative to the position of the tree, such that a relatively even distribution of litter can be expected within a stand of *Acacia nilotica* trees and for a radius around a single tree. Similarly the throughfall chemistry distribution (*e.g.* figures 8.5-7) shows little evidence of stratification within the tree plots relative to tree positions. Between tree plots and control (no tree) plots the differences in the throughfall chemistry varied in effect (for July sampling - 5 elements/ionic species significant, 6 not-significant at $P<0.05$) suggesting effects are currently limited to a small range of elements/ionic species.

This inconsistent effect was also found with the inputs from weed plants. Whilst Kessler and Breman (1991), in discussing the potential of agroforestry trees to increase primary production in Sahelian rangelands, emphasise the synergistic effect of woody species with the "herb-layer" or annual crops, in this instance the measurements of standing dead material showed no correlation between locations with trees and without. It would appear that the distribution and growth of annual plants is most closely linked to the distribution of seeds (section 5.3.4) and to the water available for their growth.

Monitoring of below-ground interactions has been limited to the assessment of the stratification of root biomass. These results have shown that the greatest root biomass is found in the upper 20 cm of the soil, suggesting that this is the zone where greatest competition between the trees, crop plants and weed plants occurs. This emphasises the need for successful management of the soil structure to obtain greater infiltration and retention of water. Apart from allowing greater infiltration to lower zones, increases in organic matter in the surface soils may help retain water in this zone, allowing more successful intercropping.

When the temporal distribution of organic inputs to the soil from both the above-ground plant growth and from the rainfall and throughfall are considered, many significant differences throughout the year and between the start of the rainy season and the end of it have been detected (Tables 8.2-3, Figure 8.3). These will have major impacts on the subsequent fate of these nutrients, particularly in synchronising crop planting to make the best use of them and to prevent leaching and gaseous losses. This also emphasises the need for more refined (*i.e.* smaller areas - possibly at the individual tree level) sampling strategies, more frequent sampling and more detailed (disaggregated) modelling of these systems.

The implications for the New Marte site centre on the need to further refine the timing and quantities of organic inputs in order to try and modify the soil structure (Chapters 6 and 7). The SCUAF modelling showed predictable qualitative changes in the N and C cycles for the given site conditions and management of the intercropping. The plant and tree growth rates are assumed by the SCUAF model, rather than calculated, and these assumptions may limit the value of the model for quantitative predictions of the availability of C and N. However, the prediction of trends in these nutrient parameters and in soil erosion are of considerable value for land-use planning. For the conditions of the New Marte site, the SCUAF modelling has revealed that nutrient inputs through the influence of trees will produce a reduction in soil erosion over long time periods. A combination of this benefit, and the benefits gained from nutrient management by synchronised tillage, planting and biomass input, could provide a strategy similar to that proposed by TSBF guidelines for humid tropical conditions, for both enhanced crop production and tree establishment in this semi-arid region.

9 DISCUSSION AND CONCLUSIONS

9.1 INTRODUCTION

This thesis has examined a range of soils in North East Nigeria as part of a wider study of the implications of potential land-use systems, in particular agroforestry. Such studies are seen to be of immediate importance to the local population since primary production has suffered due to the twin effects of climate change and population pressure. This has resulted in greater and unsustainable exploitation of fuelwood and a reduction in the bush-fallow period, traditionally adopted in this area. Whilst the population increase since 1960 in the North East Nigeria area may be a localised problem, other Sahelian farmers have described worsening climate conditions (Cross and Barker, 1991), thereby echoing the view of Mortimore (1989) amongst others. At the local administrative and academic level (*e.g.* Satter and John, 1985) there is a wider concern for a variety of environmental issues, including risks to the production of all rain-fed crops due to less favourable meteorological conditions. In 1960 Nye and Greenland considered that the cultivation of crops by rain-fed methods in areas such as this to be a limited enterprise; such views helped to promote the large-scale irrigation schemes in this area. With the failure of such schemes and the continuing decline in rainfall, the lake floor has been more extensively used for agriculture as the lake has receded (Kolawole, 1988). This thesis has examined the range of soils found on this newly exposed area along a chronosequence of exposure.

This soil chronosequence forms a background to the more detailed studies undertaken on the agroforestry site at New Marte. Since the site was only established in 1987 there has been a relatively short time for the effects of the agroforestry planting (*Acacia sp.*, *Balanites aegyptiaca* and *Prosopis juliflora* tree species and sorghum intercropping) to have influenced soil properties, specifically physical characteristics. Therefore the examination of the soil chronosequence should provide an indication of where the soils of the agroforestry experimental site are "coming from" and "going to" in terms of their development.

In reporting both a soil chronosequence and the soils aspects of an agroforestry experiment, this thesis has examined a varied selection of soil parameters. These measurements have been used to both characterise the soils examined and to be indicative of pedogenic processes. Many of these measurements have provided a survey of the field site that can be referred to and compared with any future measurements made after longer periods, and these measurements have therefore required the use of standard analytical methods. Methods for the other measurements made have been developed to give an insight to some of the processes within the soil, and such methods are therefore considered "surrogates", since they are indirectly related to the soil process or characteristic of interest.

A wide selection of soil parameters has been studied over a range of spatial levels, from regional (>100 km) to the intra-experimental plot level (1-25 m). All of these measurements have been subsequently statistically analysed, either to further characterise the soil or to examine the effect of the tree-planting on the New Marte site. Additionally, at the site-level and plot-level, when soils parameters with a spatial component have been measured, these data have been analysed using spatial geostatistical techniques in order to complement the interpolated mapping of these parameters. In addition, measurements on infiltration and on nutrient inputs have been made.

9.1.1 Plan of Chapter

This chapter discusses the issues arising from the measurements made at each of the three spatial scales: regional chronosequence (> 100 km), inter-plot site-level (25-400 m), and intra-plot level (1-25 m). The site-level measurements include data of tree performance and the plot-level measurements include infiltration and nutrient input measurements in addition to soil measurements. A separate appraisal of the results is made in section 9.6, where the farming systems of North East Nigeria are compared with other systems in sub-Saharan Africa. This is followed by discussion of the key results and their possible implications for local farmers and for land use, with particular reference to agroforestry. The chapter concludes with suggestions for further experimentation as well as commentary on the applied aspects of the research.

9.2 REGIONAL LEVEL RESULTS

9.2.1 Context of experimentation

The general context of the experimentation is that outlined in Chapter 1: increased population pressures and a diminishing water regime are leading to the degradation of soil and land resources in the region of North East Nigeria. The basis of the agroforestry experimentation at New Marte has been focused on these two factors and has aimed to increase fuelwood supply and optimally utilize available rainfall for crop production. The effects consequent on climatic changes in this region have been considered by many authors as limiting to plant growth, particularly crops. If the current climate trend accelerates, however, the resistance of trees to increased heat/drought will reach a limit and their survival will also be threatened. For instance, many of the *Acacia* species and Baobab (*Adansonia digitata*) are adapted to their current climate and are able to resist ground fires and prolonged drought periods (Collinson, 1977), but it is evident from further north in the Sahel (Roose, 1992) that these trees would not survive chronic conditions of increased aridity. The observation by Foster (1914) of many *Acacia* stands in the North East Nigeria region contrasts strongly with the small number of relict trees seen presently. There is little doubt that a combination of both climate and human factors have been involved in the reduction in tree coverage of this region.

The above-ground effects of changes in climate and changes in land-management are, obviously, more visible than any effects below-ground. Nevertheless, soils of the whole of West Africa have been considered in relation to both crop and tree growth for many years (*e.g.* Moss, 1968). There has been, however, a pronounced shift from the agricultural technologies promoted during the 1950's and 1960's towards more sustainable systems which do not use artificial nutrient inputs and high-technology irrigation systems. With this shift in agricultural thinking, the study of soils has become of even greater importance since many aspects of farming management are now dependent upon the maintenance of soil resources, through both prevention of erosion and maintenance of fertility and at both regional and local (field) levels.

In the North East Nigeria region the management of the lacustrine-derived soils for the infiltration and retention of water is of special concern since the area would be unable to sustain sorghum cropping if there were not large quantities of water in the upper aquifers originating from drainage further afield, rather than from local rainfall. The physical properties of the soils which may relate to these moisture characteristics were therefore of particular interest throughout this thesis. These physical properties have been studied at all spatial levels, but with the greatest emphasis placed on the detailed plot-level experimentation.

9.2.2 Characterisation of soil profiles in chronosequence

Whilst no dating either by radiochemical or thermoluminescence could be undertaken, the series of profiles (Chapter 2) would appear to fit into a presumed chronosequence, where the radial distance (*i.e.* 0, 45, 70, 120 km) from the current (1995/6) lake margin to the sampling position is indicative of the relative length of exposure. This presumption is supported by the physical properties of the soil samples (Chapter 3), including properties indicative of increasing ped strength (field description of ped shape) indicative of more prolonged pedogenesis in the older exposures.

9.2.3 Summary of regional results

The descriptions of the profiles from Baga, New Marte, Kala and Ngeje indicate a trend of increasing ped strength and increasingly strong vertisolic features with increasing age within the chronosequence (Chapter 2). This field impression is only partially reinforced by the results of physical analyses (ped shrinkage, aggregate stability), but not by the more varied chemical analysis results (Chapter 3) with the parent material dominating the characteristics of these samples. Since the parent materials for these soils are similar, the key factor in the classification of these profiles is the moisture regime of the site. The youngest exposures and the wettest conditions were found at Baga where the soils are classified as Ustic Aquepts. This is chronologically followed by the three New Marte profiles which are all classified as Ustic Aquicambids. Finally the two oldest profiles at Kala and Ngeje are both classified as Usterts. These USDA soil classification terms, therefore, indicate the more pronounced pedogenesis of the older profiles from an "inceptisol" to a "vertisol" (Section 2.6.4) in addition to the dryer moisture regime experienced at the sites of the older profiles. Since the major differences between these sites are the period of exposure and the moisture regime, this suggests that the New Marte site is coming from an inceptisol and going towards a vertisol, as the soil develops with increasing age; as such it could be called a "proto-vertisol".

Whilst there are large areas world-wide where vertisols have developed, these soils which are developing on the lacustrine deposits of a receding Lake Chad are distinctive because of their variable, but limited, depth of clay (*i.e.* <1.6 m) (Section 1.6.3). Vertisols elsewhere in Africa are reported with greater clay depths (*i.e.* >2.0 m) and with evidence of gilgai features (*e.g.* Kenya and Sudan - van De Weg, 1987). In other parts of the world gilgai features are considered commonplace in vertic soils (Dudal, 1965; Probert *et al.*, 1987) but, along with other vertic features such as slickensides, they were only found as "micro-gilgai" at the Kala and Ngeje sites (Section 2.6.3), suggesting that either greater clay depth is required or a longer period since exposure for these vertic features to become more pronounced.

9.3 NEW MARTE SITE-LEVEL RESULTS

The work undertaken across the New Marte site is described in Chapters 2, 3, and 4 of this thesis. At this site-level, this comprises of a characterisation of the heterogeneity of the surface soils and of measurements of other factors such as tree performance. Additionally, to characterise the vertical heterogeneity of these soils, three profiles were examined. In this section the results of these measurements are discussed in relation to each other and to relevant parameters measured at the plot-level such as infiltration (Chapter 7) and nutrient inputs (Chapter 8).

9.3.1 Characteristics of New Marte soil profiles

The three New Marte profiles all reveal features emphasising the parentage of the solum: lacustrine deposits overlain with varied depths of windblown sand. A particular feature is the continuous massive sand layers in the lower zones of each profile. The surfaces of the sand-rich soil profile "NM 1" and the more silty "NM 2" profile have laminated surface crusts which are much stronger than the immediate underlying layer. Such crusting may inhibit initial water infiltration to this soil and generate water run-off. No surface crusting is found on the clay-rich surface of profile "NM 3". This combination of soil crusts developing on higher points of the site topography (Figure 4.5), could create conditions where rainfall run-off from these areas is accelerated relative to areas where there is disturbance due to plant growth. The use of a hoeing cultivation on these sandy soils (section 7.2.3) produced no effect on the infiltration measurements. This suggests that the underlying features, including root systems, channelling and turbation by soil meso-fauna and relict features produced by lacustrine fauna, are the determining factor in non-ponded infiltration of these areas of soil with sand-rich surfaces. Furthermore, the horizontal water movement is a likely cause of further crust formation (Valentin, 1992) on neighbouring areas. It is also likely that the run-off induced by the surface crusting will lead to decreased initial infiltration in these areas relative to the clay-rich surface areas, where the vertic cracks allows considerable infiltration during the initial rains (*cf.* Chapter 7).

Previous studies show severe root restriction in other clay soils when air-filled porosity is low (*i.e.* < 0.1 cm^3 cm^{-3} ; Probert *et al.*, 1987), such as in the massive soil horizons found in all three New Marte profiles. The coring for gravimetric moisture and root biomass (section 8.4) revealed a minimal root presence (0.1 g/dm^3 in positions close to trees) in these lower zones compared with the surface zones (3.4 g/dm^3 in positions close to trees). It can be postulated therefore, that either the roots are restricted by the massive structure of these sand and mixed sand/clay layers, or there is sufficient water in the upper zones in the periods when the plant are extending their root systems. The competition between the planted trees and the sorghum crop is therefore further compounded by these soil features in addition to their seeking water.

The chemical properties of the New Marte profiles show trends which correlate with the soil texture measurements, principally sand content. In profile "NM 1" the electrical conductivity measurements down the profile show a large increase with depth (< 0.05 mS/cm at depths < 1m; > 0.20 mS/cm at depths > 1 m). These appear to correspond to zones of increased clay content, and decreased permeability, with the result that soluble salts are deposited here increasing the electrical conductivity. In all profiles, there is only a small quantity of detectable calcium carbonate (found only at depths >1.25 m in NM 1 profile) suggesting that carbonate deposits are limited to depths where water movement has been restricted, or has experienced chronic waterlogging, and salt deposition has taken place.

Despite the correlation between the chemical parameters and soil texture, for all three New-Marte profiles, there appears to be no direct relationship between texture and the horizontal penetration resistance of each profile zone. The penetration resistance therefore acts as an indicator of the development of a structure within massive sedimentary layers of parent material, *i.e.* it acts a surrogate measurement of soil structure. The textural characteristics of the soil profiles show varying amounts of sand, silt, clay and fine clay. The clay to fine clay ratio varies considerably, and may represent discrete clay depositional events in the formation of the parent material. There is no evidence to suggest that the clay has been generated by pedogenic activity. From these profile measurements it is therefore concluded that soil development has been restricted to the uppermost zones (0-40 cm) of these profiles.

9.3.2 Site-wide chemical and physical surface soil characteristics

The chemical and physical analysis of the site-wide surface (0-10 cm) samples has enabled a range of interpretative techniques to be employed (section 4.5). These have ranged from interpolated mapping, calculation of the rate of change in a parameter along two orthogonal axes (*cf.* Table 4.1), principal component analyses, to the production and interpretation of semi-variograms (Figures 4.1, 4.17). All these methods confirm that the dominating feature of these results is the very distinct general trend across the site of the soil texture: ranging from sands in the NE corner of the site to a heavy clay in the SW corner. The perceived reason for this trend occurring is the input of aeolian sand from the prevailing NE wind direction. Qualitative field observation of the movement of sand particles by wind suggests that saltation is the main mechanism of sand movement. The gradation of the surface sand layer therefore, may be seen to be a combination of both wind and water effects where sands are being brought into the site by wind action but are not accumulating on the lower-lying clay areas because of surface water erosion.

The strong, significant ($P<0.05$) correlations of the physical soil parameters (sand, silt, clay, fine-clay, bulk density) to each other extend also to some of the chemical properties considered (Table 4.2). As in the soil profiles, the electrical conductivity shows positive correlation with clay content, but unlike the profile chemistry, it is not as strongly reflected by the pH values with fewer significant ($P<0.05$) correlations. The addition of organic material to the surface soil may therefore be seen to be influencing these results, but the overall trends seen in the mapping, variograms and tabulated data remain dominated by their correlation to soil texture. The results of both the physical and chemical measurements are consistent with values quoted for other vertisols world-wide (Probert *et al.*, 1987) and with previous surveys in this area (Beavington, 1978).

A statistical analysis of the soil colour measurements was made in an attempt to use this descriptive parameter in a more objective manner, to differentiate soil texture or organic components. In addition to the Munsell colour system, an alternative system, less commonly used for colour comparison, CIE $_{1931}$ was included in the statistical correlation analyses. Whatever system of soil colour measurement was used, there were significant correlations ($P<0.05$) of these measurements with the soil texture parameters, principally silt content, and with loss-on-ignition. Since the loss-on-ignition will vary due to both the organic and the clay content of these surface soils, the soil colour measurements did not provide a substitute for either of these soil factors. However, the methodology could be used in other situations, particularly where the soil parentage does not vary as much as the surface-soil texture on the New Marte site.

9.3.3 Summary of site-wide results with respect to agroforestry

The influence of the soil properties was tested against the survival of the trees planted for the agroforestry experimentation. This revealed that the quantity of sand or clay was related to tree survival, an effect seen in the mapping of these parameters (section 4.6.1) and in the tabulated results (table 4.1). Other parameters, including bulk density and those which followed the trend of the soil texture, mirrored these differences. The poor tree-survival in the clay rich areas may be due to a wide variety of factors, but the more prolonged water-logging that the clay rich and topographically lower area experiences is likely to be a particularly important factor. It may be considered desirable to find a readily measured variable that indicates the potential of the soil for tree planting; since the presence or absence of a sand layer is used in the local naming of soils (*cf.* section 3.1.2) it is appropriate to consider this approach. When a selection of soil parameters not including soil texture were tested together as a co-variate in the analysis of tree survival and tree growth (cross-sectional area), no significant differences ($P<0.05$) were found (section 4.6.7), strengthening the view that soil texture is the dominant factor in tree performance.

Whilst the texture of the soil is the major factor in both the chemical properties inherited and in the performance of the tree planting, the depth of the sand layer is surprisingly not significant ($P<0.05$) in its relation to tree survival whereas the topographic height is significant. This reinforces the suggestion that the duration of waterlogging is the most important factor for plant growth. Erosion by surface water could conceivably physically remove planted trees in their first year of growth, but after this initial period chronic waterlogging will lead to anoxic conditions and the death of trees. Furthermore these results suggest that even on sandy soils, the underlying clay layers play the most significant part in influencing the water regime of the soil, since even soils with deep surface sand are waterlogged for prolonged periods, but because they are higher topographically the trees show greater survival. In the design of future experiments, and in extension work with local farmers the recognition of soil variability and its effects on trees needs to be considered. In particular the planting techniques adopted may need to be tailored to the specific soil conditions encountered, both on the surface and at depth. A key could be usefully developed with these site-wide survey results as its basis, suitable for use by local farmers or by extension workers, that allows soil conditions to be matched to the species of tree most likely to succeed in these conditions.

9.4 PLOT-LEVEL RESULTS

9.4.1 Introduction

Further to characterising the soils at New Marte at the site level, the relationship between soils and the planted *Acacia nilotica* trees in the agroforestry experiment at New Marte has been explored by the use of quantitative soil structural, physical and chemical measurements within the plot experimentation. The measurements made and the analysed results are discussed in chapters 5, 6 and 7 of this thesis. These observations revealed that there are several statistically significant ($P<0.05$) observable differences in soil properties between plots planted with *Acacia nilotica* trees and control plots without trees.

For any significant differences between tree-plots and control-plots to become apparent, differences due to the inherent heterogeneity of the soil must be overcome. The results of both physical and chemical analyses have shown relatively large variations in soil properties over short, intra-plot (1 m - 25 m) distances over all eight of the plots considered at the New Marte experimental site. This heterogeneity is seen in the site topography (figure 5.10) as well as the mapping (figures 5.18 - 5.31) and the semi-variograms (figure 5.37) of both the physical (*i.e.* bulk density, penetration resistance, depth of surface sand layer) and the chemical (*i.e.* N, P, pH, EC, OM) measurements. The semi-variograms show no trends or patterns at these short lag distances compared to the trends evident at the site level. This is particularly evident in the depth of surface-sand, where the NE - SW trend found at the site level is not seen in the plot level measurements.

Apart from characterising the heterogeneity of the soils at this plot-level, a number of other measurements have been undertaken. These include *in situ* sampling of soils for structural analysis by image analysis techniques, classification of flora, infiltration experiments relative to surface conditions and tree position, and measurements of nutrient inputs.

9.4.2 Soil Structure

Analysis of the soil sections taken from *in situ* resin cast blocks of soil reveals (Chapter 6) significant differences in the area, perimeter and shape of soil pores between sections from tree-influenced positions and those from control plots.

Several alternative methods of analysis were used, including a quantitative fractal method and an image ranking procedure. The fractal analysis, although suggesting the same trend of increased pores in tree plots (*i.e.* smaller aggregates) as the conventional image analysis method, did not reveal these as being significant ($P<0.05$). Likewise the image-ranking procedure revealed no significant differences but suggested instead that each person viewing the sections distinguished between them using differing criteria, suggesting that image analysis using scanned or photographed sections and electro-mechanical interpretation is required in order to make quantitative comparisons of soil structure. The other physical property measured at the plot-level was the wet aggregate stability of soils. The results from these experiments indicate that the method adopted is precise and was not operator dependent. The results show that there are no significant differences in the aggregate stability between tree and control plots suggests that the soil aggregates are being "disturbed" in some manner by the trees; possibly physically by roots or by inducing meso-faunal activity.

9.4.3 Other soil physical measurements

The infiltration measurements made on a variety of plots (Chapter 7) show significant ($P<0.05$) differences in the steady state infiltration rate between tree and control plots in the sandy soils. They do not, however, show differences due to the proximity of a tree relative to the sampling position, when infiltration experiments are carried out at a smaller spatial scale (1-3 m) within individual tree plots. In another separate experiment, the surface condition of the soil was used as an experimental treatment (tilled/not-tilled). This experiment revealed no differences due to the tillage, reinforcing the opinion that the texture of the underlying layers influences infiltration and hence water-logging and the survival of trees. When the clay-rich soils were measured, despite no visually evident surface cracking, catastrophic initial infiltration occurred (see section 7.4.4). The water was "poured" into cracks extending from the soil surface to depth which were only observed after the application of water in the infiltrometer. This suggests that even weakly developed cracking clay soils, and soils where cracks are not evident on the surface such as at New Marte, can allow large quantities of water to infiltrate until they swell and the cracks close. Since the clay layer is comparatively shallow (0.4 m *vs.* 2.0 m at Kala and Ngeje) the water infiltrating is more likely to be transferred to the underlying sand layers and ultimately to the groundwater. If greater quantities of water are found to be reaching the groundwater as a result of tree planting then this may feed-back to provide prolonged water supplies for deep rooting plants *i.e.* the trees themselves, throughout the dry season. If this effect is large enough and long term, and if sufficiently large areas were planted with trees, then the water level of Lake Chad may also be affected with increased groundwater recharge. However, this effect is likely to be insignificant compared to the effects of upstream damming and irrigation from the major rivers.

Penetration resistance across the plots differed, increased resistances being observed in tree plots (sections 5.3.3 and 5.7.2). This is most likely because of accelerated soil drying. Penetration resistance measurements on both the plots and the profiles (section 2.6.3) have also revealed the formation of a surface soil crust in many locations. In semi-arid regions such soil crusting is particularly important as a factor in the calculation of area infiltration, since the sealing of a soil surface by the development of a crust accentuates water run-off. At regional levels, the presence or absence of a sealing soil crust is considered more important in modelling water infiltration than the nature of the soil matrix itself (Valentin, 1992). Soil crusting is also often discussed in terms of being a problem for the germination and emergence of plant seeds. At New Marte with the cultivation of masakwa sorghum, this is not the case since the crop is transplanted rather than grown from directly planted seed. This procedure allows sequential batches of seedlings to be raised and fertilized from the period of the first few rains of the season onwards. This in turn allows the period of growth to be matched to the rainfall received and to the water available by altering the timing of the transplantation.

Whilst the colour of the clay fractions, extracted for the assessment of mineralogy, is indicative of nontronite (Chapter 3), the colour measurements made on surface soil samples at the site level, like the results at the plot level, have not revealed particularly striking results and do not act as the surrogate of any other single measurement. The method developed for this thesis would, however, appear to be applicable for more strongly developed soils with pronounced soil colours *e.g.* Oxisols, where the colours due to the clay and organic contents are not so uniform as at New Marte.

Such attempts at finding surrogate measurements for soil parameters are necessary if low-technology low-cost methods, which are readily applied in the field or simply equipped laboratories, are to be found. If a suitable surrogate measurement is found, the number of soil samples that can be analysed increases, with consequent improvements in their characterisation. Since the procedures required for the image analysis measurements are lengthy it would be desirable to find a suitable alternative measurement. In many soils bulk density is a suitable indicator (Landon, 1991). In this instance bulk-density measurements at both the site and plot level revealed some parallels with the textural trends but not with the other structural measurements, leading to the conclusion that the cracking in the more fine-textured clay-soils balances the massive structure of the coarser-textured sandy areas. Consequently, the bulk-density measurements cannot be considered a good surrogate indicator of the soil's structural characteristics.

9.4.4 Plot-level soil chemical properties

The plot-level chemical measurements on surface soil samples have revealed a varied spatial distribution which is expressed in the mapping (section 5.5.2) and in the scattered distribution of points in the variograms (section 5.6.4). With such variability to be overcome before an effect is apparent, it is therefore not surprising that only two (Organic matter, Total P) of the nine variables considered showed significant ($P<0.05$) differences between tree and control plots. These results also showed a lack of small-distance trends whereas, at the larger spatial area of the whole site, trends in the chemical variables were apparent in the mapping (section 4.6.1; with north-south and east-west directional trends shown in table 4.1) and in the semi-variograms (section 4.6.6). This heterogeneity is seen in both the analyses of the surface (0-10 cm) soils and in the lower (10-50 cm) samples. This would suggest that the effects of variable additions to the soil surface are expressed at depths greater than 10 cm since greater uniformity would be expected in a layer, since at greater depths this soil has a layered stratigraphy (section 2.5).

9.4.5 Nutrient inputs

The spatial distributions of nutrient inputs to the soil appear particularly difficult to map at spatial levels smaller than the plot (*i.e.* at <25 m), with none of the measurements made (Chapter 8) showing stratification within the tree plots. In comparisons between the tree and control plots there are, however, a number of throughfall inputs (K, Mg, Si, NO_3^-) showing significant ($P<0.05$) differences at each sampling (section 8.4.1). The throughfall chemistry shows differences in the major plant nutrient elements due to the interception by the tree canopy, and the rainfall chemistry throughout the rainy season also shows temporal differences.

With all these temporal and spatial differences combined, the effect of trees may require longer periods to become apparent. There is also a suggestion that the organic component of the throughfall and in particular the stemflow from *Acacia nilotica* is allelopathic to the surrounding vegetation; this may, in turn, reduce the quantity of organic material supplied by such plants to the soil and as a result reduce aggregate stability and the strength of pedogenic soil structures. Such a speculation may warrant further investigation before use of this *Acacia* species is made with an intercrop.

Since the agroforestry experimentation has been superimposed upon an area of soils which already shows heterogeneity at the larger site scale, there are several management implications both for agroforestry experimentation and for local farmers. Principal amongst these are the interactions between the performance of individual trees and variations in soil properties. It was demonstrated that, at this intra-plot level and over an initial experimental period of six years, there are several significant tree/soil interactions. Establishing trees in relation to such small-scale variability of soil properties rather than using regular planting configurations is suggested as a possible means of improving the precision and practical relevance of agroforestry experiments. In Niger, Chase and Boudouresque (1987) report that farmers both recognise the small-scale changes in soils and react to this in their practices, particularly in the management of organic materials (tree prunings, crop residues, animal and household manures). This is similar to the organic matter management strategies promoted by the TSBF initiatives in East Africa.

9.5 DISCUSSION OF METHODS USED

9.5.1 Physical and chemical analytical methods

The wide range of methods used for analysis were all chosen with two main criteria. Firstly, the methods adopted were required to be readily reproducible so that baseline measurements can be repeated reliably. Standardised USDA, FAO or SSEW methods were adopted wherever practical and reporting of results followed the recommendations of these organisations and of Landon (1991). Secondly, the least complex (*i.e.* a low technology) method was sought in order to both improve the reproducibility and to be more readily transferable to other experiments on different sites.

A variety of sampling methods was used. For soil samples these ranged in complexity from auger extraction of an approximate volume of surface soil material (section 4.3) to sampling of resin-impregnated soil blocks for the image analysis work (section 6.2). Using steel rings for the sampling for bulk density measurements was found to be particularly difficult during the dry season, with the soil likely to crumble and break within and around the ring. For the *in situ* sampling of soil blocks, where sampling was necessary in the dry season this was overcome by excavating around the sample tin. The apparatus used to take samples of other materials were all fabricated locally: the sand traps (Chapter 3) were constructed from standard plumbing fittings and the collectors used to take the biomass and water samples (Chapter 8) were derived from apparatus described in the TSBF handbook (Anderson and Ingram, 1993).

Whilst the laboratory chemical analyses have all been performed using recognised standard procedures, the physical measurements required methods tailored for the soil conditions. The wet sieving procedure was developed and sieve sizes selected to suit the particular soil conditions. The replication found in the independent experiments using this procedure suggests that this method can be used for comparison either with future measurements at New Marte or measurements made using the procedure described of samples from elsewhere, rather than limiting these results to a "snapshot" comparison of the effect of trees (section 6.6).

Likewise, since there is no accepted standardised image analysis method, the method described in section 6.2 was developed to suit both the field conditions and the equipment and materials available in the laboratory. The lack of a world-wide standardised procedure makes comparison of results from the samples described in this thesis and results gathered by other authors difficult. Whilst this can be partially overcome with summary parameters such as the calculated fractal dimension of the soil pores, the adoption of a standardised method by a major soil science organisation would facilitate more objective comparisons between experiments and between soil types of parameters of specific interest. This could be envisaged to be of particular value where soil management practices using different cropping or cultivation techniques are being considered and results are available from different sources. Unfortunately, in the short-term this standardisation is unlikely, since the derivations of such summary values are themselves not standardised.

9.5.2 Mapping and statistical methods

In common with the physical and chemical analyses, standard methods have been applied where possible in the presentation of data through mapping and in the statistical analysis of data. The recommendations of Tufte (1983), on the style of presenting graphical information have been followed. The mapping using UNIRAS (1990), of the site-level and plot-level data (Chapters 4, 5, 6, 7, 8; raw data Appendix V) used a standardised interpolation procedure, with uniform class intervals selected according to the range, rather than a population function (*i.e.* more classes around mean value of data), of the data set. The statistical analysis of these data with a spatial component has again used standard methods to produce comparative mean and standard error values. Additionally, the calculation and plotting of semi-variograms using SAS (1991) has allows a more detailed analysis of spatial trends.

Other data presented in the thesis have either not been analysed statistically (*e.g.* soil profile data, plant species distribution) or have again been processed using standard methods. In the case of the treatment of the image analysis data (Sections 6.3.4; 6.4.2), since there is no standardized practice of describing the pores or calculating summary variates, the only statistics performed were those of calculating the means and standard errors of these values.

9.6 SUMMARY OF WORK AND ITS IMPLICATIONS FOR LOCAL FARMERS AND LAND-USE POLICY

9.6.1 Spatial and Temporal changes in land-use strategies

In any land-use system, farming practices utilize different niches at different spatial levels. This is evident in many discussions of agricultural practice (*e.g.* IITA, 1993) from tropical home-gardens to range-land management. In common with many of the world's semi-arid regions the region is typified by many factors creating spatial differences in land-use, including: localised rainstorms and below-ground water resources; drainage; grazing patterns of pastoralists; and socio-geographical factors such as road transport. The spatial variations in land characteristics, particularly soil properties, are apparent at a variety of different levels and these have been examined in various detail in the central chapters of this thesis for the North East Nigeria region.

When comparing land-use strategies of this region with other tropical areas, it is self-evident that there are major differences, particularly with regard to the climate. Johnson and Lewis (1995) note that land-use strategies for semi-arid areas must withstand wider fluctuations in moisture conditions than more humid locales. This implies that tillage and planting must accommodate climatic factors in their timing, whereas humid areas are not so constrained. In the Sahel region there are several techniques used by farmers to manage their land according to the rains received. These include the use of different crops and plant spacing (Lamers *et al.*, 1995) which in turn may help alleviate conditions where desertification is probable (De Troyer, 1986). However, the utilization of water drained from elsewhere, rather than rainfall, to supply the needs of the crops grown is an important factor in distinguishing North East Nigeria from regions of similar climate in the Sahel. In these other areas strategies include extensive use of water harvesting around individual plants (Roose, 1992) whereas in North East Nigeria bunding systems normally extend to field boundaries.

On other soils in the Sahel region, crop growth has been found to vary at spatial scales relevant to the farmer. (Brouwer *et al.*, 1992,1993; Geiger and Manu, 1993). Lamers *et al.*, (1995) report that farmers have been found to exploit variations in soil properties by matching plant requirements to micro-site niches, both that which is inherent and that caused by the presence of trees, particularly legumes (Nicou, 1986;

Virginia, 1986), and other perennial woody vegetation. Scoones *et al.* (1996) in East Africa have recorded changes in the spatial management of a wide variety of crops at both farm and field level and have found similar management practices occurring, albeit in more humid climatic conditions. In the area of study in North East Nigeria, many changes in agricultural practice are related to political factors rather than farmer-choices since there have been major interventions in land management, particularly the Chad Basin irrigation projects. The Chad Basin projects themselves though have identified different small land areas (<50m) exploited by farmers and thereby (in terms of CBDA plans) requiring different irrigation needs (Hansen, 1966).

9.6.2 Management of nutrient inputs

For Sahelian agriculture systems, Amanor (1994) has reported that the observed decrease in soil organic matter over the last twenty years is due mainly to changes in farming practices where farmers have resorted to permanent cultivation rather than shifting (swidden) bush-fallow rotations. The reduction in crop rotations and the consequent loss of nutrient input or retention during the fallow period has led to major initiatives to develop robust alternatives (Scholes *et al.*, 1994). Studies elsewhere in sub-Saharan Africa have included novel intercropping and management of organic material inputs (Anderson and Ingram, 1993; Swift *et al.*, 1994).

There is therefore, an implicit trend towards promoting intensification of farmer practices, changing from bush fallow to annual cultivations and multiple cropping. These last two systems have greater requirements for labour, due to increased land preparation, manuring, weeding and management of fodder (Table 9.1). Whilst, in many humid areas these are possible to achieve, the extensive nature of Sahelian agricultural practices, including those found in North East Nigeria, may make such systems unworkable. The systems adopted by the local farmers around New Marte fall currently between the "bush-fallow" and the "short-fallow" classes of Meertens *et al.*, (1995) shown in Table 9.1. This is in contrast to a longer bush-fallow reported in this area and described by Tuley, *et al.* (1972), thereby suggesting that an intensification of the farming systems locally adopted has occurred.

Table 9.1 Farming systems comparison for sub-Saharan Africa
after Meertens *et al.*, (1995).

Operation	**Farming system**				
	Forest Fallow	Bush Fallow	Short Fallow	Annual Cultivation	Multiple cropping
Land clearing	Fire	Fire	None	None	None
Land preparation	None	Hoe/digging stick	Plough	Animal-drawn plough	Animal-drawn plough
Fertilisation	Ash	Ash	Animal dung	Manure, inc. green manure, chemical fertilizer	Manure, inc. green manure, chemical fertilizer
Use of animals	None	Animal - drawn plough may be used as fallow becomes shorter	Ploughing, transport	Ploughing, transport, post harvest tasks and irrigation	Ploughing, transport, post harvest tasks and irrigation
Seasonal labour demand	Minimal	Weeding	Land preparation, weeding and harvesting	Land preparation, weeding and harvesting	Peak demand for land preparation, weeding, harvesting and post-harvest
Supply of fodder	None	Some grazing land	Abundant open grazing	Stubble grazing	Intensive fodder management and production of fodder crops

New Marte -
Indigenous farming systems combine aspects of both the bush fallow and short fallow categories

9.6.3 Dynamics of North East Nigerian agricultural systems

The land-use system found at any point should not be assumed to be static, and temporal changes in land-use have been identified and classified in many ways around the world. A Malthusian view, equating population pressure with increased resource demand, has been extended to look at how land-use may change from one farming system to another due to population pressures. Boserup (1965) stated a hypothesis where fallow rotational cropping systems may change to intensive annual cropping to meet the demands of an increasing population. Latterly other social, cultural and political interactions with the farming system, implemented in the field, have become the source of much debate in literature discussing agricultural practices in sub-Saharan Africa (*e.g.* IITA, 1993; Scoones *et al.*, 1996). Meertens *et al.*, (1995), using a case study of a Tanzanian province, conclude that agricultural development is influenced by five inter-determinant factors: population density, ecology, economics, political policy and agricultural technology .

Whilst the population density of the Sahel region remains lower than that of more tropical areas, the rate of population growth in the Sahel region is high: in the 30 year period 1950-1980 the population of the region has doubled (World Bank, 1990), with the rate predicted to rise further. Policies to try and limit the growth in population are now being implemented by agencies such as the World Bank and by national governments although only in 1988 did the Chad government finally repeal a French Colonial law banning contraception. The ability for a given area to support a given population, the so-called "carrying capacity", has been exceeded for all of the Sahel region, increasing the risk of both desertification and diminished food supply (Mabbutt, 1984; Baumer, 1990). Whilst factors influencing the increase in population, such as better medical care, are common throughout the Sahel, N.E. Nigeria has seen an increase due to other factors including the resettlement of workers on the CBDA projects. That these projects have been seen to fail (Adams, 1992), has led to what could be termed an increasingly marginalized population (Blaikie, 1985), dependent upon more traditional, but still intensive, forms of agriculture.

For the North East Nigeria region, and in common with the change in population, the change in meteorological patterns appears to be a phenomenon that has accelerated in the past half-century. Since the major ecological impacts on crop-plants and trees are associated with the quantity and distribution of rainfall, problems of diminishing annual rainfall are therefore confounding problems associated with increasing population.

The economic factors in the case study of Meertens *et al.*, (1995) centred on the changes in the quantity of cotton (*Gossyium hirsutum)* grown. In North East Nigeria a wide variety of crops are produced including cotton, but the changes in production of ground-nuts (*Arachis hypogaea*) as a cash crop are more indicative of the shifts of Nigerian agricultural and transport policies. Both the rail and road building policies of the colonial and national governments respectively helped to promote the production of ground-nuts in Northern Nigeria (Iliffe, 1995), but following the drought periods of the early 1970's and 80's this production has much diminished, with Nigeria's economy now based on oil extraction rather than agriculture. The main agricultural policy affecting the North East Nigeria region has been the promotion of rural development, from rice production schemes implemented by the colonial administration (McClintock, 1992), through a variety of administrative organisations post-independence (Adams, 1992), resulting in the implementation of the Chad Basin irrigation schemes.

In creating new policies for the agricultural development of this region, any technical requirement should be capable of being fulfilled with local materials and labour, since the complex "agricultural-technology" route that the CBDA irrigation projects promoted has been seen to fail (Adams, 1992; Kirscht, 1996). The farming-systems-research (referred to as "FSR" in some sources) approach to developing new methodologies in agricultural development, bases its decisions on socio-economic factors as well as agricultural factors. Recently, some authors (Meertens *et al.*, 1995) have tried to modify the static viewpoint of this approach to include future technical innovation by local farmers which is often dismissed from current planning. Before any agroforestry system, such as that at New Marte, could be suggested as an alternative agricultural practice in North East Nigeria, a farming-systems-research approach suggests that it should be considered in conjunction with the social and economic factors. Where this has been undertaken in farmer trials of intercropping systems elsewhere, the amount of labour input required has often been found to be prohibitive (Smaling, 1993). This last argument follows that of Boserup (1965), where it is predicted that an increasing population must compensate shortages of usable land with increasing labour inputs. This highlights one possible reason for the relative lack of adoption of newly introduced intensive agricultural and agroforestry technologies in sub-Saharan Africa. It is suggested by Meertens *et al.*, (1995) that alternative technologies should only be promoted by extension workers where local economic factors including labour inputs are similar to the existing situation.

Some populist commentators consider Malthusian rhetoric as indicative of "doom and gloom" with apocalyptic scenarios constructed to provide a driving force for interventionist, and often prescriptive, development initiatives. Such use of "crisis narratives" in development literature is considered a result of this Malthusian rhetoric emphasising the population pressure upon finite natural resources (Reij *et al.*, 1996). This is common in many discussions of soil erosion and land degradation where soil loss is considered paramount, whereas the emphasis may really need to be directed at nutrient depletion, labour inputs and marketing for the agricultural produce (Stocking, 1996).

Agroforestry practices are often very labour intensive and require a great deal of management. This is particularly true of hedgerow intercropping systems. In the experiment at New Marte, the use of indigenous species of trees and crops in the system design allows greater inputs of local farming knowledge to be used. With the success of the crop particularly dependent upon the timing of the crop transplantation this would be a major advantage if the system were to be adopted by local farmers. The labour input required to the New Marte agroforestry system could be minimised if the planting and growth of the trees with an sorghum crop were limited to few cropping years, before the trees were prohibitive to successful cropping (*i.e.* by shading, below-ground nutrient and water resource competition, and roosting of such granivorous birds as *Quelea quelea*).

In contrast, some agroforestry systems may involve greater demands of labour than can be supplied by the local populus. This has been used as an argument to suggest that the Malthusian argument is flawed, such that where areas of increasing population are able to supply the greater labour inputs required for more complex intensified farming systems, including agroforestry, this situation contains an element of sustainability. Examples of such studies include Harris (1996) working in the environs of Kano, Northern Nigeria and Tiffen *et al.* (1994) considering soil erosion in Kenya. However, when considering nutrient balances, these works have been undertaken in relatively short time periods and they acknowledge (Harris, 1996) that net nutrient depletion through "soil mining" in these areas (*e.g.* Kenya; Smaling, 1993) may be operative over longer periods. The rôle of nutrient management is therefore prominent in many current debates of agricultural development of sub-Saharan Africa.

9.7 POSSIBILITIES FOR FUTURE RESEARCH WORK

Whilst soil considerations impinge on many aspects of land management, other experiments in sub-Saharan Africa (*e.g.* for a discussion of work undertaken at IITA see Dashiell *et al.*, 1993) have demonstrated that there is a wide variety of subjects to be considered in any agricultural or forestry developmental work. The work undertaken and described in this thesis allows comments only on soils-related issues, in particular soil characterisation over the lacustrine plains of the Chad Basin and the influence on them of the agroforestry trees at New Marte.

The experimental site at New Marte is a major resource and the mapping of the soil properties across this site at various scales forms an initial "baseline" set of measurements which should be compared with a future set of measurements on samples taken when the trees will be more fully mature. Changes in both physical and chemical properties would be expected to be evident. Methods that have been used in both the chemical and physical characterisation of the soil follow standard procedures as simplified as possible, with the aim of increasing their reproducibility by reducing operator dependence. Where "customised" procedures have been adopted (*i.e.* aggregate stability, image analysis of sections) they have shown high levels of reproducibility between independent experiments, thereby assuring that repeated measurement after longer periods will be valid.

If the trees can be protected and left to grow, the influence of their biomass input on soil structure could be assessed as another "snapshot" in, say, 10 - 20 years time. If the trend suggested in the chronosequence from inceptisols towards vertisols is followed, it would be expected that the small differences found so far in soil structural characteristics on the field site, should then be more pronounced. For instance the soil aggregate stability, which does not show significant differences, would be expected to become greater under the stresses induced by rainfall and water accumulation on the soil surface. Furthermore, the soil structural features quantified in the sections taken would be anticipated to show clearer distinctions between plot treatments.

The processes involved in the incorporation and redistribution of the biomass inputs are an obvious subject for further study, since such processes will impact upon both the cycling of nutrients (C, N, P) and, as has been demonstrated (Chapter 7), these inputs will also influence the infiltration water. The activities of the soil meso-fauna appear to be dominated by termites and ants, but neither their populations, nor their rôle has been studied in this thesis. However, these insects are likely to be the major cause of any vertical and horizontal redistribution of organic material deposited by the tree planting at New Marte, so any future work should include experimentation to gain some understanding of the rôle of soil meso-fauna in this process. This may allow more refined and synchronised management of crop residue and tree pruning inputs.

This thesis has also emphasised the variable heterogeneity of the studied areas, with distinct trends across the New Marte site but none evident at the smaller plot-level. This heterogeneity is utilised by local farmers in order to maintain some cropping in adverse growing conditions, where crop failure on one area and soil type may be partially compensated by a crop growing on another area with different characteristics (Lamers *et al.*, 1995). This emphasises both the need to characterise in detail the soils of experiments such as at New Marte and also the difficulties in overcoming these variations at small spatial scales in order to detect soil changes due to the experimentation. Studies such as those reviewed by Lamers *et al.* (1995), also show the need to incorporate indigenous knowledge of soil types and their uses. In North East Nigeria preliminary studies have recently been undertaken and reported (see section 3.1.2) by ethnographers (Kirscht and Skorupinski, 1996). Although these local soil/land-use classifications vary between villages, they may be useful in future resource management initiatives where a particular soil/land-use class could be promoted for a specific objective (*e.g.* tree-planting with development of suitable establishment methods).

Whilst the agroforestry experimentation at New Marte has, most recently, been concentrated upon improving investigated methods of tree and crop management to increase fuelwood supply and to optimally utilize available rainfall, future investigations may include other needs. Recently, studies of soil erosion have been undertaken at small intra-field levels (Strömquist, 1992), as well as the more established field and catchment levels. This thesis has shown the importance of inputs of aeolian material to the soils of this region; this suggests that further studies on both the interception of material and the prevention of material loss through wind erosion by individual trees and tree stands is of special importance. The action of tree planting on the reduction of soil erosion and deposition by water movement when the area is flooded is also of interest, since both solid soil material, particularly organic litter, and leached nutrients will be redistributed.

9.8 CONCLUSION

The aim of the work undertaken and described in this thesis (section 1.3.1) was to characterise and produce an account of the soils at the New Marte agroforestry field site, within the context of the presumed chronosequence across the lacustrine clay plains of North East Nigeria. The major surface features visible in these soils are the differences between the soils where there has been aeolian sand deposition and areas where the surface is characterised by cracking clays. These regional differences, long recognised in previous soil surveys, have been highlighted throughout the plot experimentation at the New Marte site.

The site-level and plot-level soil surveys are possibly the first undertaken in Africa at this scale. In combining the soil survey data with the information on initial tree performance a base-line for future comparisons has been made. The need to maintain such field experiments over the medium to long term (10-20 years), so that predictive models and soil-tree interactions may be judged, must be emphasised.

The major pedogenic factors identified have, to varying degrees, been examined. The influence of aeolian sand deposition on the soil parent material is reflected in the topography of the New Marte site. Such changes in topography are shown to be important in the redistribution of surface materials during the rainy season at the site level, and are also likely to be significant in any catchment-wide analysis of nutrient and sediment distribution. The plot-level experimentation has revealed significant differences between soil samples attributable to the presence of trees, with changes in physical properties more evident than in chemical properties.

Most notably, the image analysis of soil structural features reveals several significant differences attributed to the presence of trees, and it is predicted that this action by the trees will promote structural development towards the strong ped features observed in the oldest profiles exposed within the chronosequence. It is reasonable to assume that this process will become more marked over periods longer than the six years of tree growth considered. Similarly, a longer period may allow the tree planting to produce effects on the soil chemistry and nutrient inputs that overcome the inherent heterogeneity encountered and quantified at short lag distances between sampling positions. There is already an indication with several of the measured variables, that the trees are having a significant effect on the soils, and it is expected that over longer periods a greater number of the measured variables will show significant differences.

Appendix I

ABBREVIATIONS AND ACRONYMS USED

B.G.S.	British Geological Survey
B.P.	Before present
BSI	British Standards Institute
CABI	C.A.B. International - formerly Commonwealth Agricultural Bureaux
CAR	Central African Republic
CAST	Council for Agricultural Science and Technology [of the USA]
CBDA	Chad Basin Development Authority [of Nigeria]
CIE	Commission Internationale de l'Eclairage [International commission on illumination]
CIRAD	Centre Internationale de Recherche en Agronomie et en Dévelopement
COLE	Co-efficient of Linear Expansion
CSIRO	Commonwealth Scientific and Industrial Research Organisation [Australia]
DMSO	Dimethylsulphoxide
d.p.i.	Dots per inch
DTA	Differential Thermal Analysis
EDM	Electronic Distance Measurement
e.s.d.	Equivalent Spherical Diameter
e.s.e.	Equivalent Standard Error
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FSR	Farming Systems Research
FT-IR	Fourier Transform Infra-Red analysis
GIS	Geographical Information System
GPS	Global Positioning System
GTZ	Gesellschaft für technische Zusammenarbeit [German development aid organisation]
HDPE	High-density polyethylene
IBSRAM	International Board for Soil Research and Management
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectroscopy/Spectrograph
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IIED	International Institute of Economic Development
IITA	International Institute of Tropical Agriculture
INERA	Institut National d'étude et de Recherches Agronomiques du Burkina Faso
ILCA	International Livestock Centre for Africa
IRRI	International Rice Research Institute
ISCO	International Soil Conservation Organisation
ISSS	International Society of Soil Science

KIT	Royal Tropical Institute of The Netherlands
MAB	Man and the Biosphere programme [of (*cf.*) UNESCO]
MAFF	Ministry of Agriculture, Fisheries and Food
MEK	Methyl-Ethyl Ketone (Propan-1-one)
MIT	Massachusetts Institute of Technology
NEAZDP	North-East Arid Zone Development Programme [EU funded project in Nigeria]
NPP	Net Primary Production
n.s.	Not Significant [with probability (P) less than stated value]
O.D.	Ordnance Datum
ODA	Overseas Development Administration
ORSTOM	Institut français de recherche scientifique pour le dévelopement en coopération
P	Probability - quoted with value
PVC	Polyvinyl chloride
RH	Relative Humidity
SADCC	Southern Africa Development Co-ordination Conference
SCUAF	Soil Changes Under Agroforestry [model developed by (*c.f.*) ICRAF]
SD	Standard Deviation
s.e.d. or SED	Standard Error of the Difference between mean values
SSEW	Soil Survey of England and Wales
STP	Standard temperature and pressure (25 °C , 1 atm)
TDR	Time Domain Reflectrometry
TSBF	Tropical Soil Biology and Fertility [a component of (*c.f.*) MAB programme]
USLE	Universal Soil Loss Equation
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNSO	United Nations Sudano-Sahelian Office
USDA	United States Department of Agriculture
USGS	United States Geological Service
WASWC	World Association of Soil and Water Conservation
WCED	World Commission on Environment and Development
WRI	World Resources Institute
XRDA	X-ray Diffraction Analysis

Appendix II

LOOK-UP TABLE TO CONVERT MUNSELL COLOUR TERMS TO CIE 1931 COLOUR SPACE COORDINATES

This table is restricted to the Munsell colour terms found in the standard Munsell Soil Color Charts (Munsell Color Company, 1975). Conversion values taken from Travis (1991) and Newhall *et al.* (1943).

7.5R

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4118	0.3385	0.5910
8	6	0.3830	0.3335	0.5910
8	4	0.3564	0.3279	0.5910
8	2	0.3277	0.3211	0.5910
7	8	0.4196	0.3382	0.4306
7	6	0.3888	0.3336	0.4306
7	4	0.3611	0.3282	0.4306
7	2	0.3335	0.3220	0.4306
6	8	0.4318	0.3383	0.3005
6	6	0.4000	0.3340	0.3005
6	4	0.3692	0.3291	0.3005
6	2	0.3381	0.3228	0.3005
5	8	0.4563	0.3387	0.1977
5	6	0.4180	0.3348	0.1977
5	4	0.3806	0.3294	0.1977
5	2	0.3425	0.3229	0.1977
4	8	0.4850	0.3359	0.1200
4	6	0.4415	0.3340	0.1200
4	4	0.3990	0.3300	0.1200
4	2	0.3538	0.3236	0.1200
3	8	0.5251	0.3297	0.06555
3	6	0.4738	0.3316	0.06555
3	4	0.4240	0.3302	0.06555
3	2	0.3690	0.3248	0.06555
2	8	0.5433	0.3027	0.03126
2	6	0.4875	0.3123	0.03126
2	4	0.4335	0.3169	0.03126
2	2	0.3751	0.3181	0.03126
1	8	0.5722	0.2487	0.01210
1	6	0.5235	0.2698	0.01210
1	4	0.4660	0.2888	0.01210
1	2	0.4020	0.3034	0.01210

10.0R

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4212	0.3526	0.5910
8	6	0.3910	0.3442	0.5910
8	4	0.3621	0.3349	0.5910
8	2	0.3301	0.3237	0.5910
7	8	0.4308	0.3533	0.4306
7	6	0.3984	0.3452	0.4306
7	4	0.3671	0.3360	0.4306
7	2	0.3360	0.3253	0.4306
6	8	0.4449	0.3550	0.3005
6	6	0.4103	0.3473	0.3005
6	4	0.3768	0.3381	0.3005
6	2	0.3417	0.3268	0.3005
5	8	0.4713	0.3575	0.1977
5	6	0.4299	0.3499	0.1977
5	4	0.3879	0.3398	0.1977
5	2	0.3465	0.3278	0.1977
4	8	0.4995	0.3557	0.1200
4	6	0.4535	0.3500	0.1200
4	4	0.4078	0.3412	0.1200

4	2	0.3582	0.3294	0.1200
3	8	0.5393	0.3477	0.06555
3	6	0.4854	0.3467	0.06555
3	4	0.4308	0.3412	0.06555
3	2	0.3728	0.3314	0.06555
2	8	0.5713	0.3259	0.03126
2	6	0.5095	0.3331	0.03126
2	4	0.4481	0.3330	0.03126
2	2	0.3811	0.3274	0.03126
1	8	0.6178	0.2713	0.01210
1	6	0.5584	0.2921	0.01210
1	4	0.4933	0.3068	0.01210
1	2	0.4128	0.3154	0.01210

2.5YR

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4275	0.3662	0.5910
8	6	0.3960	0.3547	0.5910
8	4	0.3667	0.3429	0.5910
8	2	0.3334	0.3276	0.5910
7	8	0.4371	0.3679	0.4306
7	6	0.4053	0.3570	0.4306
7	4	0.3715	0.3439	0.4306
7	2	0.3392	0.3298	0.4306
6	8	0.4533	0.3708	0.3005
6	6	0.4180	0.3600	0.3005
6	4	0.3806	0.3467	0.3005
6	2	0.3453	0.3321	0.3005
5	8	0.4795	0.3758	0.1977
5	6	0.4365	0.3640	0.1977
5	4	0.3925	0.3494	0.1977
5	2	0.3506	0.3337	0.1977
4	8	0.5071	0.3777	0.1200
4	6	0.4612	0.3674	0.1200
4	4	0.4141	0.3539	0.1200
4	2	0.3624	0.3367	0.1200
3	8	0.5475	0.3771	0.06555
3	6	0.4954	0.3692	0.06555
3	4	0.4360	0.3563	0.06555
3	2	0.3757	0.3391	0.06555
2	8	0.5995	0.3590	0.03126
2	6	0.5280	0.3581	0.03126
2	4	0.4598	0.3508	0.03126
2	2	0.3852	0.3365	0.03126
1	8	0.6721	0.3058	0.01210
1	6	0.6048	0.3270	0.01210
1	4	0.5311	0.3371	0.01210
1	2	0.4258	0.3344	0.01210

5.0YR

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4310	0.3820	0.5910
8	6	0.3988	0.3663	0.5910
8	4	0.3690	0.3510	0.5910
8	2	0.3373	0.3330	0.5910
7	8	0.4402	0.3842	0.4306
7	6	0.4091	0.3701	0.4306
7	4	0.3750	0.3530	0.4306
7	2	0.3421	0.3349	0.4306
6	8	0.4592	0.3900	0.3005
6	6	0.4229	0.3750	0.3005
6	4	0.3840	0.3564	0.3005
6	2	0.3474	0.3373	0.3005
5	8	0.4830	0.3960	0.1977
5	6	0.4420	0.3808	0.1977
5	4	0.3968	0.3614	0.1977
5	2	0.3530	0.3395	0.1977
4	8	0.5070	0.3994	0.1200
4	6	0.4651	0.3859	0.1200

4	4	0.4187	0.3679	0.1200
4	2	0.3651	0.3442	0.1200
3	8	0.5456	0.4040	0.06555
3	6	0.4966	0.3908	0.06555
3	4	0.4376	0.3715	0.06555
3	2	0.3771	0.3476	0.06555
2	6	0.5426	0.3925	0.03126
2	4	0.4674	0.3738	0.03126
2	2	0.3880	0.3476	0.03126
1	4	0.5660	0.3795	0.01210
1	2	0.4377	0.3580	0.01210

7.5YR

Value	Chroma	CIE *x*	CIE *y*	Y
9	8	0.4220	0.3930	0.7866
9	6	0.3950	0.3763	0.7866
9	4	0.3679	0.3585	0.7866
9	2	0.3380	0.3377	0.7866
8	8	0.4306	0.3952	0.5910
8	6	0.4000	0.3770	0.5910
8	4	0.3699	0.3586	0.5910
8	2	0.3395	0.3379	0.5910
7	8	0.4415	0.3996	0.4306
7	6	0.4107	0.3820	0.4306
7	4	0.3772	0.3613	0.4306
7	2	0.3437	0.3397	0.4306
6	8	0.4596	0.4064	0.3005
6	6	0.4242	0.3876	0.3005
6	4	0.3860	0.3652	0.3005
6	2	0.3487	0.3421	0.3005
5	8	0.4820	0.4141	0.1977
5	6	0.4440	0.3954	0.1977
5	4	0.3991	0.3714	0.1977
5	2	0.3540	0.3445	0.1977
4	8	0.5038	0.4204	0.1200
4	6	0.4655	0.4029	0.1200
4	4	0.4208	0.3809	0.1200
4	2	0.3662	0.3504	0.1200
3	8	0.5390	0.4306	0.06555
3	6	0.4930	0.4116	0.06555
3	4	0.4378	0.3865	0.06555
3	2	0.3771	0.3549	0.06555
2	6	0.5475	0.4271	0.03126
2	4	0.4690	0.3964	0.03126
2	2	0.3889	0.3590	0.03126
1	2	0.4430	0.3775	0.01210

10.0YR

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4280	0.4102	0.5910
8	6	0.3994	0.3896	0.5910
8	4	0.3701	0.3674	0.5910
8	2	0.3407	0.3434	0.5910
7	8	0.4399	0.4164	0.4306
7	6	0.4102	0.3960	0.4306
7	4	0.3778	0.3719	0.4306
7	2	0.3443	0.3454	0.4306
6	8	0.4570	0.4249	0.3005
6	6	0.4240	0.4030	0.3005
6	4	0.3861	0.3767	0.3005
6	2	0.3491	0.3483	0.3005
5	8	0.4770	0.4338	0.1977
5	6	0.4428	0.4128	0.1977
5	4	0.3995	0.3840	0.1977
5	2	0.3546	0.3514	0.1977
4	8	0.4965	0.4414	0.1200
4	6	0.4618	0.4213	0.1200
4	4	0.4189	0.3948	0.1200
4	2	0.3660	0.3590	0.1200
3	8	0.5305	0.4559	0.06555

3	6	0.4872	0.4326	0.06555
3	4	0.4341	0.4018	0.06555
3	2	0.3747	0.3630	0.06555
2	4	0.4676	0.4168	0.03126
2	2	0.3872	0.3688	0.03126
1	2	0.4446	0.3982	0.01210

2.5Y

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4231	0.4231	0.5910
8	6	0.3969	0.4009	0.5910
8	4	0.3684	0.3751	0.5910
8	2	0.3406	0.3484	0.5910
7	8	0.4353	0.4312	0.4306
7	6	0.4073	0.4073	0.4306
7	4	0.3761	0.3800	0.4306
7	2	0.3436	0.3507	0.4306
6	8	0.4517	0.4421	0.3005
6	6	0.4203	0.4176	0.3005
6	4	0.3840	0.3867	0.3005
6	2	0.3480	0.3540	0.3005
5	8	0.4685	0.4524	0.1977
5	6	0.4380	0.4292	0.1977
5	4	0.3968	0.3954	0.1977
5	2	0.3534	0.3570	0.1977
4	8	0.4865	0.4625	0.1200
4	6	0.4542	0.4391	0.1200
4	4	0.4138	0.4076	0.1200
4	2	0.3633	0.3654	0.1200
3	6	0.4784	0.4531	0.06555
3	4	0.4277	0.4166	0.06555
3	2	0.3703	0.3700	0.06555
2	4	0.4627	0.4392	0.03126
2	2	0.3825	0.3785	0.03126
1	2	0.4362	0.4177	0.01210

5.0Y

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4158	0.4378	0.5910
8	6	0.3913	0.4117	0.5910
8	4	0.3650	0.3826	0.5910
8	2	0.3394	0.3518	0.5910
7	8	0.4271	0.4462	0.4306
7	6	0.4009	0.4198	0.4306
7	4	0.3718	0.3885	0.4306
7	2	0.3419	0.3540	0.4306
6	8	0.4426	0.4588	0.3005
6	6	0.4140	0.4305	0.3005
6	4	0.3794	0.3955	0.3005
6	2	0.3457	0.3580	0.3005
5	8	0.4579	0.4692	0.1977
5	6	0.4302	0.4435	0.1977
5	4	0.3915	0.4057	0.1977
5	2	0.3500	0.3620	0.1977
4	8	0.4745	0.4810	0.1200
4	6	0.4451	0.4550	0.1200
4	4	0.4069	0.4188	0.1200
4	2	0.3590	0.3701	0.1200
3	6	0.4670	0.4711	0.06555
3	4	0.4191	0.4283	0.06555
3	2	0.3646	0.3748	0.06555
2	4	0.4543	0.4573	0.03126
2	2	0.3757	0.3839	0.03126
1	2	0.4230	0.4265	0.01210

7.5Y

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4088	0.4466	0.5910
8	6	0.3862	0.4175	0.5910
8	4	0.3622	0.3861	0.5910
8	2	0.3379	0.3540	0.5910
7	8	0.4184	0.4568	0.4306
7	6	0.3943	0.4264	0.4306
7	4	0.3677	0.3925	0.4306
7	2	0.3396	0.3558	0.4306
6	8	0.4321	0.4719	0.3005
6	6	0.4060	0.4400	0.3005
6	4	0.3745	0.4004	0.3005
6	2	0.3431	0.3601	0.3005
5	8	0.4450	0.4850	0.1977
5	6	0.4199	0.4551	0.1977
5	4	0.3850	0.4120	0.1977
5	2	0.3470	0.3640	0.1977
4	8	0.4595	0.4990	0.1200
4	6	0.4331	0.4688	0.1200
4	4	0.3982	0.4272	0.1200
4	2	0.3542	0.3727	0.1200
3	6	0.4526	0.4889	0.06555
3	4	0.4086	0.4379	0.06555
3	2	0.3589	0.3778	0.06555
2	4	0.4401	0.4723	0.03126
2	2	0.3660	0.3858	0.03126
1	2	0.4042	0.4287	0.01210

10.0Y

Value	Chroma	CIE *x*	CIE *y*	Y
8	8	0.4008	0.4520	0.5910
8	6	0.3803	0.4216	0.5910
8	4	0.3581	0.3883	0.5910
8	2	0.3359	0.3552	0.5910
7	8	0.4090	0.4641	0.4306
7	6	0.3864	0.4305	0.4306
7	4	0.3624	0.3951	0.4306
7	2	0.3369	0.3569	0.4306
6	8	0.4201	0.4812	0.3005
6	6	0.3960	0.4452	0.3005
6	4	0.3679	0.4033	0.3005
6	2	0.3398	0.3611	0.3005
5	8	0.4307	0.4967	0.1977
5	6	0.4072	0.4621	0.1977
5	4	0.3762	0.4158	0.1977
5	2	0.3422	0.3648	0.1977
4	8	0.4430	0.5153	0.1200
4	6	0.4190	0.4795	0.1200
4	4	0.3871	0.4321	0.1200
4	2	0.3476	0.3732	0.1200
3	6	0.4345	0.5026	0.06555
3	4	0.3961	0.4452	0.06555
3	2	0.3513	0.3789	0.06555
2	4	0.4188	0.4789	0.03126
2	2	0.3556	0.3848	0.03126
1	2	0.3802	0.4212	0.01210

2.5GY

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3327	0.3555	0.5910
7	2	0.3328	0.3569	0.4306
6	2	0.3342	0.3607	0.3005
5	2	0.3352	0.3636	0.1977
4	2	0.3382	0.3706	0.1200
3	2	0.3412	0.3768	0.06555
2	2	0.3421	0.3803	0.03126
1	2	0.3540	0.4088	0.01210

5.0GY

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3284	0.3542	0.5910
7	2	0.3284	0.3559	0.4306
6	2	0.3288	0.3592	0.3005
5	2	0.3289	0.3612	0.1977
4	2	0.3312	0.3678	0.1200
3	2	0.3319	0.3729	0.06555
2	2	0.3309	0.3743	0.03126
1	2	0.3359	0.3982	0.01210

7.5GY

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3194	0.3502	0.5910
7	2	0.3190	0.3516	0.4306
6	2	0.3193	0.3550	0.3005
5	2	0.3188	0.3560	0.1977
4	2	0.3185	0.3604	0.1200
3	2	0.3180	0.3644	0.06555
2	2	0.3165	0.3650	0.03126
1	2	0.3154	0.3840	0.01210

10.0GY

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3121	0.3459	0.5910
7	2	0.3117	0.3469	0.4306
6	2	0.3112	0.3496	0.3005
5	2	0.3110	0.3508	0.1977
4	2	0.3109	0.3550	0.1200
3	2	0.3088	0.3578	0.06555
2	2	0.3069	0.3580	0.03126
1	2	0.3006	0.3720	0.01210

5.0G

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3009	0.3359	0.5910
7	2	0.3001	0.3366	0.4306
6	2	0.2988	0.3382	0.3005
5	2	0.2978	0.3392	0.1977
4	2	0.2959	0.3417	0.1200
3	2	0.2935	0.3439	0.06555
2	2	0.2918	0.3450	0.03126
1	2	0.2833	0.3564	0.01210

10.0G

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.2957	0.3293	0.5910
7	2	0.2945	0.3297	0.4306
6	2	0.2929	0.3303	0.3005
5	2	0.2910	0.3310	0.1977
4	2	0.2880	0.3327	0.1200
3	2	0.2844	0.3337	0.06555
2	2	0.2820	0.3341	0.03126
1	2	0.2689	0.3407	0.01210

5.0BG

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.2919	0.3228	0.5910
7	2	0.2898	0.3225	0.4306
6	2	0.2872	0.3219	0.3005
5	2	0.2841	0.3210	0.1977
4	2	0.2799	0.3208	0.1200
3	2	0.2742	0.3192	0.06555
2	2	0.2697	0.3175	0.03126
1	2	0.2500	0.3141	0.01210

10.0BG

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.2894	0.3152	0.5910
7	2	0.2869	0.3143	0.4306
6	2	0.2837	0.3132	0.3005
5	2	0.2796	0.3111	0.1977
4	2	0.2740	0.3091	0.1200
3	2	0.2660	0.3050	0.06555
2	2	0.2606	0.3010	0.03126
1	2	0.2362	0.2882	0.01210

5.0B

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.2908	0.3096	0.5910
7	2	0.2875	0.3078	0.4306
6	2	0.2842	0.3063	0.3005
5	2	0.2794	0.3032	0.1977
4	2	0.2723	0.2992	0.1200
3	2	0.2617	0.2921	0.06555
2	2	0.2559	0.2874	0.03126
1	2	0.2291	0.2677	0.01210

5.0PB

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.2974	0.3039	0.5910
7	2	0.2952	0.3011	0.4306
6	2	0.2923	0.2978	0.3005
5	2	0.2882	0.2923	0.1977
4	2	0.2816	0.2842	0.1200
3	2	0.2708	0.2719	0.06555
2	2	0.2638	0.2624	0.03126
1	2	0.2427	0.2368	0.01210

5.0P

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3065	0.3047	0.5910
7	2	0.3059	0.3010	0.4306
6	2	0.3050	0.2967	0.3005
5	2	0.3045	0.2928	0.1977
4	2	0.3022	0.2825	0.1200
3	2	0.2997	0.2700	0.06555
2	2	0.2984	0.2612	0.03126
1	2	0.2936	0.2330	0.01210

5.0RP

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3180	0.3120	0.5910
7	2	0.3206	0.3104	0.4306
6	2	0.3232	0.3085	0.3005
5	2	0.3256	0.3065	0.1977
4	2	0.3310	0.3010	0.1200
3	2	0.3370	0.2940	0.06555
2	2	0.3383	0.2829	0.03126
1	2	0.3378	0.2542	0.01210

5.0R

Value	Chroma	CIE *x*	CIE *y*	Y
8	2	0.3254	0.3186	0.5910
7	2	0.3306	0.3190	0.4306
6	2	0.3343	0.3190	0.3005
5	2	0.3392	0.3192	0.1977
4	2	0.3508	0.3200	0.1200
3	2	0.3645	0.3190	0.06555
2	2	0.3692	0.3111	0.03126
1	2	0.3908	0.2929	0.01210

Appendix III

C PROGRAM FOR COLOUR SPACE TRANSFORMATIONS ADAPTED FROM TRAVIS (1991)

Note 1: Line numbering shown alongside the program below is for guidance only and is not part of the program.
Note 2: Program was written and compiled in Borland C (Borland, 1991).
Note 3: The tristimus values in the section of code from lines 12-14 and 19 will vary depending upon the output device. This could be a colour screen, printer or plotter. Methods for measuring the tristimus values are given in many texts including Travis (1991) and the standard reference work of Foley and Van Dam (1982).
Note 4: The "main" code section at lines 375 - 408 is shown here restricted to converting CIE 1931 (xyY) colour terms to RGB terms.

Program:

```
#include <math.h>
#include <stdio.h>
#define sqr(a)  (a*a)
#define PI   3.14159265358979

/*
 *  Next matrix in form xR xG xB
 *                yR yG YB
 *                zR zG zB
10 *  Where xyz are chromaticity co-ordinates
 */
double cie_xyz[9] = { .6281,  .2859,  .1535,
                      .3476,  .6091,  .0640,
                      .0243,  .1050,  .7825  };
/*
 * Next Matrix CIE XYZ of white formed by primaries
 *
 */
double cie_white[3] = {  .2965,  .3102,  .3933  };
20
/*
 * Next Matix contains tristimulus values when
 * init_tristim_matrix()
 * or init_tristrim_lum() is called
 */
double tristim[9] = { 0.0, 0.0, 0.0,
                      0.0, 0.0, 0.0,
                      0.0, 0.0, 0.0 };

30 /*
 * Following Matrix is SMITH_POKORNY fundamentals
 */
double sp_vals[9] = {0.00000, 0.00000, 0.01608,
                    -0.15514, 0.45684, 0.03286,
                     0.15514, 0.54312, -0.03286};
```

```
/*
 * Next Matrix contains RGB TO YIQ values
 */
double yiq_vals[9] = {.30, .59, .11,
                      .60, -.28, -.32,
                      .21, -.52, .31 };

/*
 *Function Prototypes
 */
int inverse(double[9], double[9]);
double det(double[9]);
void matrix_multiply(double[9], double[9], double[9]);
void vect_mult(double[9], double[3], double[3]);
void adjoint(double[9], double[9]);
int init_tristim_matrix(void);
int init_tristim_lum(double[3]);
void rgb_cie(double[3], double[3]);
void cie_rgb(double[3], double[3]);
void rgb_sml(double[3], double[3]);
void sml_rgb(double[3], double[3]);
int rgb_mb(double[3], double[3]);
void mb_rgb(double[3], double[3]);
int rgb_hsv(double[3], double[3]);
void hsv_rgb(double[3], double[3]);
void rgb_yiq(double[3], double[3]);
void yiq_rgb(double[3], double[3]);

/*
 * Compute inverse of matrix  fstmat, returned in array
 * secmat. Returns a NULL if unsucessful
 */
int inverse(double fstmat[9], double secmat[9])
{
 double d;

 if ((d = det(fstmat)) == 0) {
   return(NULL);
 }

 secmat[0] = (fstmat[4] * fstmat[8] - fstmat[7] * fstmat[5])  / d;
 secmat[1] = (-(fstmat[1] * fstmat[8] - fstmat[7] * fstmat[2]))  / d;
 secmat[2] = (fstmat[1] * fstmat[5] - fstmat[2] * fstmat[4])  / d;
 secmat[3] = (-(fstmat[3] * fstmat[8] - fstmat[6] * fstmat[5]))  / d;
 secmat[4] = (fstmat[0] * fstmat[8] - fstmat[6] * fstmat[2])  / d;
 secmat[5] = (-(fstmat[0] * fstmat[5] - fstmat[3] * fstmat[2]))  / d;
 secmat[6] = (fstmat[4] * fstmat[7] - fstmat[4] * fstmat[6])  / d;
 secmat[7] = (-(fstmat[0] * fstmat[7] - fstmat[6] * fstmat[1]))  / d;
 secmat[8] = (fstmat[0] * fstmat[4] - fstmat[3] * fstmat[1])  / d;
 return(1);
}

/*
 * Compute the determinant of the matrix
 */
double det(double mat[9])
{
 return(mat[0] * mat[4] * mat[8] - mat[0] * mat[5] *
 mat[7] + mat[1] * mat[5] * mat[6] - mat[1] * mat[3] *
```

```
  mat[8] + mat[2] * mat[3] * mat[7] - mat[2] * mat[4] *
  mat[6]);
 }

 /*
  * Given 3by3 matrix [] and a column vector [] this function
  * returns result []
  */
void vect_mult(double matrix[9], double vector[3],
double result[3])
{
 int i;

 for (i = 0; i < 3; i++)
   result[i] = matrix[i*3] * vector [0] +
     matrix[(i*3)+1] * vector[1] + matrix[(i*3)+2] *
     vector[2];
}
/*
 * Multipy two 3by3 matrices together, mat1 and mat2,
 * and put result in marix mat3.
 */
void matrix_multiply(double mat1[9], double mat2[9], double mat3[9])
{
 int i, j, k;
 for (i = 0; i < 9; i++)
 {
  j = (i < 3) ? i: i%3;
  k = (i / 3) * 3;
  mat3[i] = mat1[k] * mat2[j] + mat1[k+1] * mat2[j+3]
  + mat1[k+2] * mat2[j+6];
 }
}
/*
 * Get The adjoint of the matrix fstmat, put in secmat
 */
void adjoint(double fstmat[9], double secmat[9])
{
  secmat[0] = fstmat[0];
  secmat[1] = fstmat[3];
  secmat[2] = fstmat[6];
  secmat[3] = fstmat[1];
  secmat[4] = fstmat[4];
  secmat[5] = fstmat[7];
  secmat[6] = fstmat[2];
  secmat[7] = fstmat[5];
  secmat[8] = fstmat[8];
}
/*
 *  init_tristim_matrix()
 *
 *  This function generates the basic tristimulus matrix to initialise
 *  the program
 */
int init_tristim_matrix(void)
{
 double wht_vect[3], cie_vect[3];
 int i, j;
```

```
  if ((inverse(cie_xyz, tristim)) == NULL)
    return(NULL);
 /*
  * Compute tristimulus values of the white for the unit Y
  */
  wht_vect[0] = cie_white[0] / cie_white[1];
  wht_vect[1] = 1.0;
  wht_vect[2] = cie_white[2] / cie_white[1];

  vect_mult(tristim, wht_vect, cie_vect);
  for (i = 0; i < 9; i++)
  {
   j = i < 3 ? i : i%3;
   tristim[i] = cie_xyz[i] * cie_vect[j];
  }
  return(1);
}
/*
 * init_tristim_lum()
 *
 * This function generates the basic tristimulus matrix to
 * initialise the program given three relative luminances in
 * order red green blue Use this function as an alternative to
 * init_tristim_matrix()
 */

int init_tristim_lum(double lum[3])
{
 int i;
 double sum = 0.0;

 for(i=0; i < 3; i++)
    sum+=lum[i];

/* Chk for sensible luminance values
 */
 if(sum > 1.0 || sum < 1.0)
  return(NULL);

 for(i=0; i < 9; i++)
  tristim[i] = 0.0;

/* red gun */
 tristim[0] = cie_xyz[0] * lum[0] / cie_xyz[3];
 tristim[3] = lum[0];
 tristim[6] = cie_xyz[6] * lum[0] / cie_xyz[3];

/* green gun */
 tristim[1] = cie_xyz[1] * lum[1] / cie_xyz[4];
 tristim[4] = lum[1];
 tristim[7] = cie_xyz[7] * lum[1] / cie_xyz[4];

/* blue gun */
 tristim[2] = cie_xyz[2] * lum[2] / cie_xyz[5];
 tristim[5] = lum[2];
 tristim[8] = cie_xyz[8] * lum[2] / cie_xyz[5];

 return(1);
}
```

```
/*
 * given RGB this function returns cie (xyY)
 */
void rgb_cie(double rgb_vect[3], double cie_vect[3])
{
  double temp_vect[3];
  int i;
  vect_mult(tristim, rgb_vect, temp_vect);
  for (i = 0; i < 2; i++)
    cie_vect[i] = temp_vect[i] / (temp_vect[0] + temp_vect[1] +
                temp_vect[2]);
    cie_vect[2] = temp_vect[1];  /* Luminance */
}
/*
 * Given cie xyY vector, this fuction returns RGB co-ordinates
 */
void cie_rgb(double cie_vect[3], double rgb_vect[3])
{
  double inv_tristim[9], tristim_vect[3];

  tristim_vect[0] = cie_vect[0] * cie_vect[2] / cie_vect[1];
  tristim_vect[1] = cie_vect[2];
  tristim_vect[2] = (1.0 - cie_vect[0] - cie_vect[1]) *
     cie_vect[2] / cie_vect[1];
  inverse(tristim, inv_tristim);
  vect_mult(inv_tristim, tristim_vect, rgb_vect);
}
/*
 * Given RGB this function returns Smith_Pokorny
 * co-ordinates.
 */
void rgb_sml(double phosphor_vect[3], double
cone_vect[3])
{
  double cone_RGB[9];
  matrix_multiply(sp_vals, tristim, cone_RGB);
  vect_mult(cone_RGB, phosphor_vect, cone_vect);
}
/*
 *Given Smith-Pokorny SML returns RGB
 */
void sml_rgb(double cone_vect[3], double
phosphor_vect[3])
{
  double cone_RGB[9], RGB_cone[9];
  matrix_multiply(sp_vals, tristim, cone_RGB);
  inverse(cone_RGB, RGB_cone);
  vect_mult(RGB_cone, cone_vect, phosphor_vect);
}
/*
 *Given RGB returns HSV
 */
#define bigger(a,b) ((a > b)? a : b)
#define smaller(a,b) ((a < b)? a : b)

int rgb_hsv(double rgb[3], double hsv[3])
{
  double min, max, r_rel, g_rel, b_rel;
  hsv[0] = hsv[1] = hsv[2] = 0;
```

```
  max = bigger(rgb[0], bigger(rgb[1],rgb[2]));
  min = smaller(rgb[0], smaller(rgb[1],rgb[2]));

 /*
  * compute value if max is zero or silly value.
  */
 if (!max)
   return(NULL);
 else
   hsv[2] = max;
 /*
  * compute saturation
  */
 if ((hsv[1] = (max - min) / max) == 0)
   return(NULL);
 /*
  * compute hue
  */
 r_rel = (max - rgb[0]) / (max - min);
 g_rel = (max - rgb[1]) / (max - min);
 b_rel = (max - rgb[2]) / (max - min);

 if (rgb[0] == max) {
   if (rgb[1] == min)
     hsv[0] = 5 + b_rel;
   else
     hsv[0] = 1 - g_rel;
 }
 else if (rgb[1] == max) {
   if (rgb[2] == min)
     hsv[0] = r_rel +1;
   else
     hsv[0] = 3 - b_rel;
 }
 else {
   if (rgb[0] == min)
     hsv[0] = 3 + g_rel;
   else
     hsv[0] = 5 - r_rel;
 }
 hsv[0] *= 60;    /* hue convert to degrees */
 return(1);
 }

 /*
  * Given HSV returns RGB
  *
  */
 void hsv_rgb(double hsv[3], double rgb[3])
 {
   double sub_color, hue_step, main_color, var1, var2,
 var3;

   hue_step = hsv[0] / 60;
   if (hue_step == 6)
     hue_step = 0;
   main_color = (int) hue_step;
   sub_color = hue_step - main_color;
```

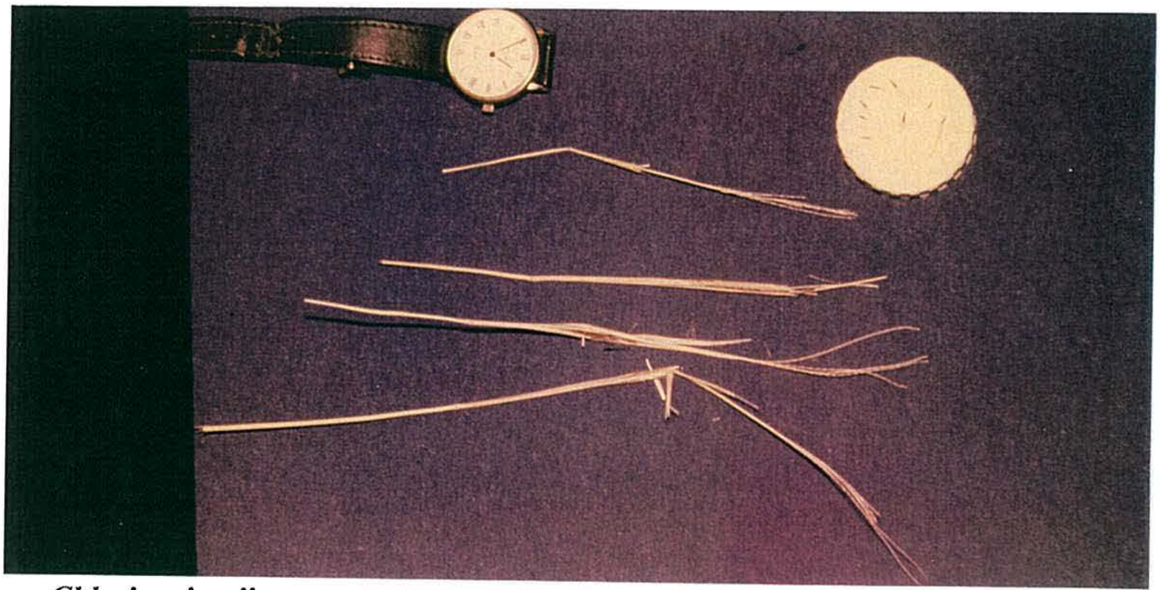
```
        var1 = (1 - hsv[1]) * hsv[2];
        var2 = (1 - (hsv[1] * sub_color)) * hsv[2];
        var3 = (1 - (hsv[1] * (1- sub_color))) * hsv[2];

        switch ((int)main_color)
        {
         case 0:    rgb[0] = hsv[2];
                    rgb[1] = var3;
                    rgb[2] = var1;
         case 1:    rgb[0] = var2;
                    rgb[1] = hsv[2];
                    rgb[2] = var1;
         case 2:    rgb[0] = var1;
                    rgb[1] = hsv[2];
                    rgb[2] = var3;
         case 3:    rgb[0] = var1;
                    rgb[1] = var2;
                    rgb[2] = hsv[2];
         case 4:    rgb[0] = var3;
                    rgb[1] = var1;
                    rgb[2] = hsv[2];
         case 5:    rgb[0] = hsv[2];
                    rgb[1] = var1;
                    rgb[2] = var2;
        }
      }
      /*
       * Given RGB, returns YIQ
       */
      void rgb_yiq(double rgb[3], double yiq[3])
      {
        vect_mult(yiq_vals, rgb, yiq);
      }
      /*
       * Given YIQ returns RGB
       */
      void yiq_rgb(double yiq[3], double rgb[3])
      {
       double inv_rgb[9];
       inverse(yiq_vals, inv_rgb);
       vect_mult(inv_rgb, yiq, rgb);
      }

void main()
{
 double vector[3],result[3];
 int ch=0,i;
 if (init_tristim_matrix()==NULL)
 { printf("Couldn't initialize program - Check with Paul\n");
   exit(1);
 }
 printf("Tristimulus matrix is:\n");
 printf("Xr=%g, Xg=%g, Xb=%g\n",tristim[0],tristim[1],tristim[2]);
 printf("Yr=%g, Yg=%g, Yb=%g\n",tristim[3],tristim[4],tristim[5]);
 printf("Zr=%g, Zg=%g, Zb=%g\n",tristim[6],tristim[7],tristim[8]);
/*
 while(ch != '1' && ch != '2');
 {
  printf("\n\t 1 rgb -> cie \n\t 2 cie-rgb \n\t\t Which Transformation ?");
```

```
    ch = getchar();
  }
 */
  ch=2;
  printf("\n Type in vector: ");
  scanf("%lf %lf %lf",&vector[0],&vector[1],&vector[2]);
  cie_rgb(vector,result);
/*  switch(ch)
  {
    case '1': rgb_cie(vector,result);
          break;
    case '2': cie_rgb(vector,result);
          break;
  }
*/
 printf("\n\t vector[%g %g %g] transforms to [%g %g %g]\n",vector[0],
      vector[1],vector[2],result[0],result[1],result[2]);
}
```

Appendix IV

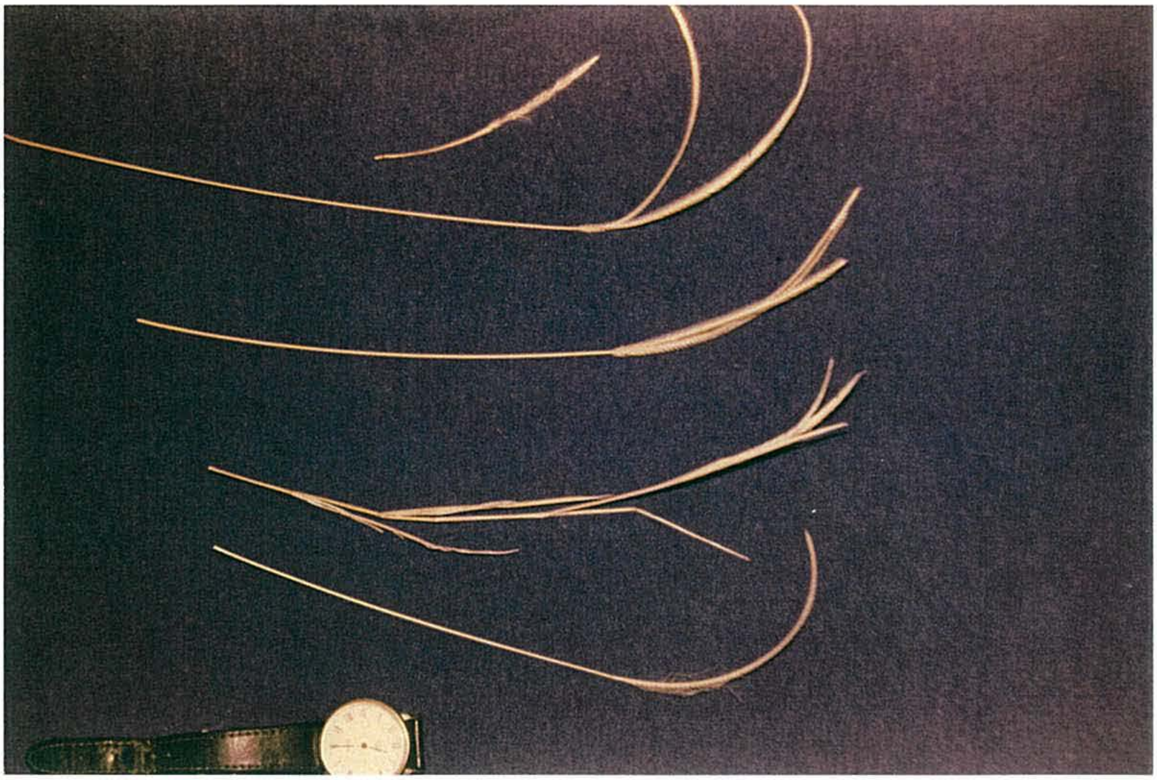
PLATES OF PLANT SPECIES IDENTIFIED AT NEW MARTE

The plates below show several of the plant species found at New Marte. These show plants found on soils which are sand-rich, intermediate and clay-rich.



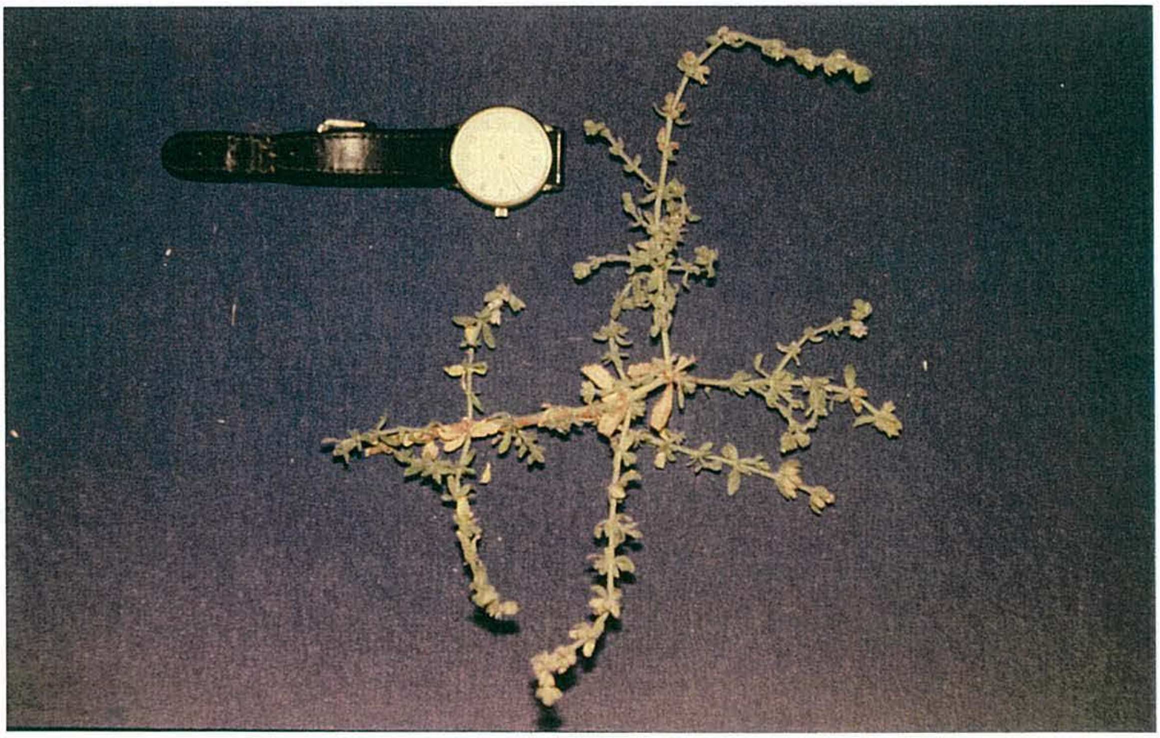
Chloris prieurii
found on soils with sand/clay intermixed surface

Sida sp.
found on clay-rich soils



Schoenefeldia gracilis
found on soils with sand/clay intermixed surface. This grass is common on the firgi plains (see section 3.2) and is used locally for thatching.

Gnaphalium sp.
found on clay-rich soils



Cassia tora
found on clay-rich soils

Sphaeranthus senegalensis
found on both sandy and clay-rich soils

Appendix V

SCUAF DATA INPUTS

The table below shows the data inputs for the SCUAF model example detailed in section 8.5. The data inputs used are a mixture of experimental results from all sections of this thesis, from quoted sources in other literature, and SCUAF default values (Young and Muraya, 1990).

Input	Option selected or value entered into model	Source of information or assumptions made
1. Cycle	2 - Carbon and Nitrogen cycles	
2. Documentation	File name: NMARTE1.SCU	
	Title: New Marte Simulation Planted Tree/ Sorghum Crop - Run 1	
	Source: Soils and below-ground biomass data only	
3. Physical environment	*SCUAF classifications*	
	Climate: 3 - lowland semi-arid	see section 1.7
	Soil texture: 3 - clayey	see section 2.4
	Drainage: 3 - poor	see chapter 7
	Soil reaction: 3 - neutral	see section 2.3
	Slope class: 2 - gentle	SCUAF class
4. Agroforestry system	Period 1,2,3,4,5,6 Length (years): 2,2,2,2,2,5 Fraction of land under tree: 0.2,0.4,0.5,0.7,0.9,1.0 Fraction of land under crop: 0.8,0.8,0.6,0.4,0.2,0.0	To simulate the growth of the trees a series of six periods are defined with the trees replacing crop area as they grow until in years 11 onward no crop is grown
	Is it a cut year?: No,No,No,No,No,No,No	Assuming no tree cutting
	What fraction of tree is N fixing?: 1.0	*A.nilotica* is a legume
	What fraction of crop is N fixing?: 0.0	Sorghum is not a legume
5. Initial Soil conditions	Topsoil depth (cm): 10	See Chapters 4 and 5 - depth consistent with sampling across site
	Soil depth considered (cm): 40	See Chapter 2 - approximate depth of zones 1&2 of profile NM 1 where meso-fauna active
	Total depth of soil (cm): 200	See chapter 2
	Initial C, topsoil (%): 0.35	See table 5.2
	Bulk density, topsoil (g/cm^3): 1.44	See table 5.2
	Initial soil C (kg/ha):	Calculated by SCUAF
	Initial N, topsoil (%): 0.067	See table 5.2
	Initial soil N (kg/ha):	Calculated by SCUAF from % N value above

6. Erosion	*USLE factors*	
	Climate factor: 260	See section 1.5 - calculated after Landon (1991)
	Soil erodibility factor: 0.2	FAO data used by SCUAF
	Slope factor: 0.4	Wischmeier and Smith (1960)
	Cover factor under tree: 0.32	FAO data used by SCUAF
	Cover factor under crop: 0.7	FAO data used by SCUAF
7. Initial plant growth	Tree, net primary production above-ground (kg dry matter/ha/yr.) : 4000	Estimate for New Marte, this corresponds to values for single *A. nilotica* trees (Grewal and Arbrol, 1986)
	Crop, NPP below-ground (kg dry matter/ha/yr) : 4000	a rough estimate
	NPP, tree leaf (kg/ha/yr) : 32	SCUAF defaults for NPP values
	NPP, tree fruit (kg/ha/yr) : 0	
	NPP, tree wood (kg/ha/yr) : 66	
	NPP, tree root (kg/ha/yr) : 40	
	NPP, crop leaf (kg/ha/yr) : 67	
	NPP, crop fruit (kg/ha/yr) : 33	
	NPP, crop wood (kg/ha/yr) : 0	
	NPP, crop root (kg/ha/yr) : 40	
	Fraction retained annually	
	tree leaf: 0	no harvesting of tree materials
	tree fruit: 0	
	tree wood: 1.0	
	tree root: 0.67	SCUAF default value
	crop leaf: 0	all above-ground growth of crop removed
	crop fruit: 0	
	crop wood: 0	
	crop root: 0	SCUAF default
	proportion of tree roots that are coarse: 0.3	*c.f.* root distribution of *A. seyal* Adams (1967)
	proportion of crop roots that are coarse: 0	
	Is any part of tree or crop retained in cut year?: No	No "cut-years" considered in this simulation
	Fraction of tree roots growing below soil depth considered: 0.2	Assuming 20% of tree roots are below 60 cm soil depth
	Fraction of crop roots growing below soil depth considered: 0	
	C fraction in dry mass, Tree: 0.5	SCUAF default value
	C fraction in dry mass, Crop: 0.5	SCUAF default value
	C:N ratio of	
	tree leaf: 20	SCUAF default values taken for C:N ratios
	tree fruit: 20	
	tree wood: 100	
	tree root: 33	
	crop leaf: 50	
	crop fruit: 20	

	crop wood: 100 crop root: 33	
8. Additions	nil for all responses	No external additions of OM or fertilizer
9. Removals	*Fraction harvested annually*	
A: Harvest	tree leaf: 0 tree fruit: 0 tree wood: 0 tree root: 0	No removal of trees or tree limbs
	crop leaf: 1.0 crop fruit: 1.0 crop wood: 0 crop root: 0	Crop including haulm harvested
B: Other losses from system	nil for all responses	No losses of tree or plant material considered for reasons other than harvesting
10. Soil Processes	*Fractional conversion losses (from Litter to Humus)*	
	Above-ground parts lost through oxidation: 0.75 Roots lost through oxidation: 0.6 Organic additions lost through oxidation: 0.6	SCUAF values for clay-rich soils
	Coarse tree roots decaying 1 year later: 1.0	default SCUAF value
	Coarse crop roots decaying 1 year later: 0	default SCUAF value
	Remaining coarse tree roots decaying 2 years later: 0.25	default SCUAF value
	Remaining coarse crop roots decaying 2 years later: 0	default SCUAF value
	Humus decomposition constants (K)	
	Number of humus fractions considered: 1	Any stable humus ignored
	Labile humus K for under tree: 0.03	after Nye and Greenland (1960)
	K for under crop: 0.04	
	Nitrogen gains	
	Symbiotic fixation per unit area of N-fixing tree (kg/ha/yr): 130	from data of other *Acacia* sp. reviewed by Giller & Wilson (1991)
	Symbiotic fixation per unit area of N-fixing crop (kg/ha/yr): 0	Sorghum does not fix N
	Fraction of symbiotic fixed N entering soil humus: 0.1	SCUAF default
	Non-symbiotic fixation (kg/ha/yr): 2	SCUAF derived value
	Throughfall and stemflow (kg/ha/yr): 3	approx. calculation from section 8.3.3
	Nitrogen losses	
	Fraction of mineral N leached under tree : 0.013 Fraction of mineral N leached under crop : 0.05	SCUAF calculated
	Fraction of mineral N lost by gaseous loss : 0.05	SCUAF default
	Fraction of mineral N lost by fixation onto clay minerals: 0.0	No evidence of N loss to clay minerals *c.f.* mineralogy - Chapter 3
11. Soil/plant feedback factors	C - tree : 0.25	SCUAF default setting
	C - crop : 0.5	SCUAF default setting
	N - tree : 0.25	SCUAF default setting
	N - crop : 0.5	SCUAF default setting
	Soil depth - tree : 0 Soil depth - crop : 0	soil depth assumed constant

Appendix VI

RAW DATA

The raw data for all levels of measurement made, from regional level soil profiles to plot level experimentation at the New Marte field site are made available in a standard computer readable media as read-only CD-ROM. This is bound within the thesis hard covers. The CD-ROM was compiled using standard equipment complying with "Yellow Book" ISO CD-ROM standards. The disk (readme.txt) and the tables are annotated such as to be self-documenting.

REFERENCES

A

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