AN INVESTIGATION OF FACTORS CONTRIBUTING TO SOIL DEGRADATION UNDER DAIRY FARMING IN THE TSITSIKAMMA

by

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ABSTRACT

Pasture-based dairy farming is the major land use in the Tsitsikamma region of the Eastern Cape. Permanent kikuyu grass (*Pennisetum clandestinum*) dominates pastures in the region. Kikuyu pastures do not, however, provide adequate year-round quality feed for dairy cows. This has led to the use of annually sown pastures with perennial ryegrass (*Lolium perenne*) to provide winter forage. Soil degradation under this management has, however, become recognised as a major limitation. Soil quality and degradation under annual and permanent pasture in the region were evaluated in three separate studies. These were (i) an investigation of the extent of loss of soil organic matter and related soil microbial properties and aggregate stability under annual pastures, (ii) a comparison of soil physical properties under annual and permanent pastures and (iii) a survey of the nutrient status of soils and pasture herbage in the region.

In the first study, four commercial dairy farms, situated on sites which represented the three main soil groups in the region were sampled. Samples were taken from under permanent kikuyu pastures, annual ryegrass pastures and undisturbed native vegetation nearby. In comparison with undisturbed, native vegetation, soils under both annually cultivated and permanent pasture had gained soil organic matter on the sandy, low rainfall eastern end of the Tsitsikamma. By contrast, at the higher rainfall, finer-textured, western end, where the native vegetation consists of coastal forest, there was a loss of soil organic matter under both types of pasture. Despite this, soil organic C content was lower under annual ryegrass than permanent kikuyu pasture at all the sites reflecting the degrading effect of annual cultivation on soil organic matter. As a consequence, labile, K_2SO_4- extractable C, microbial biomass C, basal respiration, arginine ammonification, flourescein diacetate hydrolysis rates and aggregate stability were all less under annual ryegrass than permanent kikuyu pastures at all the sites.

The effects of annual ryegrass and permanent kikuyu pastures on soil physical properties and root length density were compared with those of undisturbed native vegetation on the four experimental sites. Root density and the depth of rooting were much less under annual ryegrass than under kikuyu pastures or native vegetation. There was no consistent effect of improved pastures or pasture type on bulk density and total porosity or penetrometer resistance, although annual pasture soils generally had higher bulk densities and lower total porosities than those

under native vegetation. There was a tendency for smaller saturated hydraulic conductivity and air permeability under ryegrass than kikuyu pastures, regardless of whether total porosity was higher or lower under ryegrass. This was attributed to annual cultivation and subsequent natural consolidation causing a decrease in pore continuity under ryegrass pastures. Penetrometer resistance values confirmed the presence of subsoil compacted layers at two annual ryegrass pasture sites. At one such site, subsoil tillage was effective in reducing penetrometer resistance and bulk density, increasing pore continuity (as evaluated by hydraulic conductivity and air permeability) and greatly increasing root density and rooting depth.

The nutrient status of soil and herbage from annual ryegrass and permanent kikuyu pastures sampled from 40 dairy farms in the Tsitsikamma region were evaluated. Along with the decreased organic matter content, there was a decrease in soil pH and a loss of exchangeable cations under annual pastures. Large concentrations of extractable P and sometimes exchangeable K were measured in soils under both ryegrass and kikuyu pastures and it was concluded that the rates of applied P, and sometimes K, were often excessive (particularly under kikuyu). Various nutritional problems were also identified. These included the need for Ca supplementation, particularly under kikuyu, due to the low herbage Ca concentrations. The low Ca : P ratio measured in annual ryegrass pastures, and more particularly in kikuyu herbage, highlighted the low Ca content of herbage and also the tendency of kikuyu grass to accumulate large concentrations of P. The large K concentrations and high K : Ca + Mg ratios identified in pasture herbage suggest the potential for animal nutritional problems such as hypomagnesaemia. It was concluded that although kikuyu is an excellent pasture in terms of dry matter production it tends to be deficient in Ca (and sometimes Na) and can contain prohibitively high K levels, which are likely to induce Mg deficiencies in grazing animals. The micronutrient concentrations in herbage were generally adequate, although copper concentrations tended to be low suggesting that fertilizer applications and/or feed supplementation is required.

It was concluded that annual conventional tillage results in a substantial loss of soil organic matter, soil microbial activity and aggregate stability under annual ryegrass pastures when compared to those under permanent kikuyu grass. This loss of soil organic matter can result in natural consolidation of the soil in the cultivated layer and exasperated through treading by the grazing cows. The annual cultivation can also lead to the formation of a subsoil compacted layer.

Nonetheless, compaction can also occur under permanent pasture presumably due to treading damage. Careful management to avoid treading damage to pastures should be practised. In order to protect the organic matter status of annual pastures, direct drilling of such pastures should be seriously considered. In some cases, annual fertilizer P rates (and to lesser extent those of K) could be reduced considerably since the levels accumulated in the soils are excessive.

DECLARATION

I hereby certify that the research reported in this thesis is my own work, except where otherwise indicated in the text, and that the work has not been submitted for a higher degree in any other university.

Signed: ....

R.M. MILNE

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CHAPTER 1

GENERAL INTRODUCTION AND STUDY OBJECTIVES

The Tsitsikamma district in the Eastern Cape, South Africa, extends from the Krom river in the east to the Bloukrans river in the west. The selected study area extended from the Klipdrif river in the east to the Storms river in the west. The geology of the Tsitsikamma shows an origin of predominately Table Mountain Sandstone, with a narrow strip of Bokkeveld shale that exists from Witelsbos, west towards the Bloukrans river (Eastern Cape Farming Manual, 1984). Table Mountain Sandstone generally gives rise to sandy soils, which are evident throughout most of the region.

The topography of the Tsitsikamma is flat to rolling and is broken by gorges which run from north to south. The major rivers that drain the Tsitsikamma are the Sand, Klipdrif, Kromme, Elands, Storms and Bloukrans rivers. Owing to the high rainfall the majority of the rivers in the Tsitsikamma are perennial. The altitude varies from sea level to approximately 350 m in the north (Eastern Cape Farming Manual, 1984). The natural undisturbed vegetation or veld ranged from false macchia in the east to Knysna forest in the west (Acocks, 1988).

Pasture based dairy farming is the major agricultural land use in the Tsitsikamma, but with the recent downturn in profits in the dairy industry farmers have been forced to focus and assess their pastoral management strategies. Kikuyu grass (*Pennisetum clandestinum*), dominates pastures in the region due to the large seed bank present in the soils , its invasive, competitive nature and its adaptability to climatic and soil conditions in the region. Unfortunately, in the Tsitsikamma, kikuyu pastures do not provide adequate, year-round, quality feed intake for dairy cows because kikuyu growth is slow during the winter period. Thus a substantial portion of most dairy farms are under alternative pastures such as perennial ryegrass (*Lolium perenne*) and annual ryegrass (*Lolium rigidum*) and/or white clover (*Trifolium repens*), to provide the necessary feed requirement. These pastures have very limited longevity and frequently become kikuyu-dominant within two to three years therefore necessitating the re-cultivation and re-sowing of the pasture. This is not economically viable in the long term, and is recognized as a major cause of soil degradation (R.J. Haynes, 2000 personal communication). This degradation, in turn, contributes to the lack of pasture longevity and current management practices have created a "vicious cycle" and practicable and economically viable solutions are needed.

The questions of soil degradation and sustainability are important and management practices need to consider the maintenance of long-term productivity even when they are not directly compatible with short-term economic or productive objectives. Degradation of the soil resource is considered a major problem in agricultural production, particularly under conventional arable production (Blevins and Frye, 1993), where the tillage practices result in considerable losses of organic matter which can have detrimental effects on soil physical, chemical and biological properties. Soil organic matter is essential for the functioning of the soil as a whole, and changes in soil organic matter provides the primary measure for determining which direction current management practices are headed (Gregorich *et al.*, 1994; Karlen and Cambardella, 1996). For example, a decrease in the soil biological activity is of particular concern (Doran and Parkin, 1994; Gregorich *et al.*, 1994) since biologically mediated processes are fundamental to the ecological functioning of soils. This goes hand in hand with the soil quality assessment concept, which uses soil quality as an assessment tool. The structural implications of a loss of organic matter are quite severe, as there is normally a close relationship between soil organic matter content and water stable aggregation in soils (Chaney and Swift, 1984; Haynes and Naidu, 1997).

The central concept of the term soil quality, is the "capacity of the soil to function" (Doran and Parkin, 1994; Doran *et al.*, 1996) and it has been selected as an appropriate assessment tool because it serves as an umbrella concept for examining and integrating relationships and functions among various biological, chemical and physical parameters that are important for sustainable agricultural systems (Karlen *et al.*, 1997).

Visual observations on commercial dairy farms in the Tsitsikamma region revealed an obvious loss of soil organic matter under annual pastures compared with permanent kikuyu pastures or native vegetation (R.J. Haynes, personal communication, 2000). This seemed to be accompanied, at least in some cases, by a loss of soil structure in the topsoil and signs of subsoil compaction immediately below the cultivation layer. In addition, agricultural consultants in the region have suggested that the loss of soil organic matter under annual pastures will have caused a decline in soil microbial activity and a resultant decrease in nutrient availability (P. Terblanche, personal communication, 2000). Some people attribute the poor ryegrass pasture production and longevity primarily to poor soil nutrient status and/or nutrient imbalances, whilst others believe loss of soil organic matter and poor soil physical conditions are the main cause. There is, however, at present, no objective data base which can be used to either verify or reject these suggestions.

The aim of this study was to obtain some objective measurements as to whether soil degradation is occurring under annual pastures, and if so, to what extent. For this purpose, sites on key indicator farms were sampled across the Tsitsikamma region and soil biological, chemical and physical indicators of soil quality were analysed under ryegrass pastures, permanent kikuyu pastures and native vegetation.

This thesis is divided into six main sections. Following this general introduction, the literature pertaining to the effects of pasture management on soil quality is reviewed in detail in chapter 2. Chapter 3 investigates and discusses the comparative effect of annual and perennial pastures on soil organic matter content related microbial properties and aggregate stability. In chapter 4 the physical characteristics of the soil profile under annual and perennial dairy pastures are outlined and considered. Chapter 5 comprises of a survey of the soil and plant nutrient status of annual and perennial pastures in the Tsitsikamma region. General discussion, conclusions and suggestions for future research are outlined in chapter 6.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

In this chapter the effects of pasture management on soil quality are reviewed in order to introduce the concept of soil quality and overlook and discuss the effects that pastoral management has on soil quality. In particular the effects of permanent kikuyu pastures are contrasted with those of annual ryegrass ones and the central role of organic matter highlighted. Where applicable, examples from arable agriculture are used to illustrate the probable effect that repeated cultivation under annual pastures will have on the soil quality.

With the increasing economic, population and social pressures of today, the need for the sustainable use of resources is increasing dramatically. It is however frightening how the soil as a resource is often overlooked, even though it is one of the most important resources on which all agriculture is either directly or indirectly dependent. The soil also functions in the maintenance of local and global environmental quality through acting as a filter and a buffer for water, air, nutrients and chemicals (Doran *et al.*, 1994).

Soils form slowly, averaging 100 to 400 years per centimetre of topsoil (Doran and Safley, 1998), this slow rate of development underlines the importance of various management decisions that effect the soil quality. Indeed the soil can be regarded as a non-renewable resource in terms of a human time-frame. The various management decisions that have been made by land users and agriculturalists are therefore responsible for the present condition of the soil. For this reason soil management practices for maintaining long term productivity need to be considered carefully even when they are not compatible with the more immediate economic or productive objectives. The degradation of the soil resource is considered a major problem in agricultural production particularly under conventional arable production (Blevins and Frye, 1993).

The development of the soil quality concept and soil quality indicators has been a breakthrough in relation to maintenance of the soil resource base (Hortensius and Nortcliff, 1991). In relation to agricultural soils, quality can simply be regarded as their fitness or ability to function, i.e. support crop growth without being degraded or otherwise harming the environment (Karlen *et al.*, 1997). This definition, based on function reflects the living and dynamic nature of soil (Karlen *et al.*, 1997). A more detailed definition will be considered below.

Soil quality indicators are objective measurements of soil condition and can be divided into physical (e.g. bulk density, infiltration capacity, aggregation), chemical (e.g. pH, electrical conductivity, nutrient content) and biological (e.g. microbial biomass, enzyme activity, earthworm activity) measurements. The development of quality indicators has generated an awareness of the importance of the soil resource as well as provided a framework for assessment of the sustainability of various soil management strategies (Doran *et al.,* 1996).

Soil quality under permanent pastoral management is often considered to range between adequate and excellent (Haynes and Williams, 1993). The soil organic matter content is usually comparable or even greater than that under undisturbed natural vegetation and as a result the soil microbial and faunal activity are characteristically high (Russell, 1986; Haynes and Williams, 1993). Fertility is usually high due to adequate fertilizer applications and reasonably efficient nutrient cycling generated by the grazing animals (i.e. a large proportion of nutrients ingested by animals are returned to the soil in the form of dung and urine) (Haynes and Williams, 1993). Sometimes soil physical impediments can develop because of treading by livestock, especially under wet conditions (Mulholland and Fullen, 1991); often the dense growth of grass roots and the high earthworm activity can to a large degree remediate such problems (Haynes, 1995).

The use of pastures that are conventionally cultivated every one or two years and then resown is a common practice within South Africa, but in terms of a world-wide basis is very unusual. The effects of annual pastures on soil quality are unclear although visual observations suggest there is a considerable loss of soil organic matter and breakdown of soil structure.

2.2 SOIL QUALITY AND SOIL QUALITY INDICATORS

2.2.1 Defining soil quality

Soil quality was recently defined by Karlen *et al*, (1997) as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation." The central concept is the "capacity of the soil to function" (Doran and Parkin, 1994; Doran *et al.,* 1996) and this reflects the living dynamic nature of soil.

The function and balance of soil quality requires an integration of three major components; sustained biological productivity, environmental quality and plant and animal health (Karlen *et al.*, 1997). The concept attempts to balance multiple soil uses (e.g. agricultural production, waste remediation, urban development, forestry, rangeland or recreational) with goals for environmental quality .

The soil quality concept was developed primarily in response to increasing concern regarding soil degradation. Degradation refers to the decline in the soil's inherent capacity to produce economic goods and perform ecological functions (Lal, 1993; Seybold *et al.*, 1999). Causes of degradation include deforestation, overgrazing, agricultural practices, overexploitation of the vegetation, and industrial activities (Seybold *et al.*, 1999). Degradation infers that sustainable practices are not being used. Sustainability deals with performance at certain acceptable levels over a given time frame and refers to the productivity and economic, social and environmental aspects of a land use system, i.e. agriculture (Seybold *et al.*, 1999). Soil quality is a key component of sustainability and the trend or direction in soil quality over time is a primary indicator of the sustainability, or of current management practices (Doran *et al.*, 1996).

An extremely important component of soil quality is the response of a soil to a disturbance. Nearly all human activities associated with land management and use can be classified as disturbances. Common disturbances associated with agriculture include loading as a result of vehicular traffic, tillage, application of fertilizers and pesticides and removal and or exclusion of competing plant species, i.e. monoculture (Haynes, 1995).

Soil resistance is defined as " the capacity of a soil to function without change throughout a disturbance" (Seybold *et al.*, 1999). The magnitude of decline in the capacity to function defines the degree of resistance to change. Soil resilience refers to the capacity of the soil to recover its functional and structural integrity after a disturbance (Lal, 1993; Seybold *et al.*, 1999). Soil quality therefore becomes a function of resistance during a disturbance and of resilience after a disturbance. Resilient and resistant systems will maintain soil quality (Seybold *et al.*, 1999).

In order to evaluate soil quality there are two major questions that need to be answered (i) how does the soil function and (ii) what indicators are appropriate for making the evaluation (Karlen *et al.*, 1997). After answering these questions a range of objective measurements of the capacity of the soil to function at full potential can be developed. These measurements are commonly referred to as soil quality indicators.

2.2.2 Soil quality indicators and their use

The importance of soil quality indicators is often underestimated and it is therefore important that the principles of the uses of these indicators and their relation to soil quality are clearly understood. It is also essential that soil quality indicators consider soil chemical, physical and biological properties, as well as their interrelation, in order to provide a realistic indication of soil condition and the effects that the present management practices are having on soil quality (Doran and Parkin, 1994; Doran and Safley, 1998).

Because the definition of soil quality is function driven, there are many different and contrasting thoughts on the choice of indicators. The indicators that are most desirable are those that are practical to use, operate over a wide range of ecological boundaries and respond rapidly, or are most sensitive to changes in soil conditions. The choice of indicators may therefore change from location to location. The challenge is to define the most useful and suitable ones for a particular situation. Below is a list complied by (Doran and Safley, 1998); that provides an overview of the expectations that indicators should fulfill.

1. Correlate well with ecosystem processes
2. Integrate soil physical, chemical and biological properties and processes
3. Be relatively easy to use under field conditions and be assessable by both specialists and producers.
4. Be sensitive to variations in management and climate.
5. Be components of existing soil data bases where possible.

Soil quality indicators must be measurable by as many people as possible, especially managers of the land, and not limited to a select cadre of research scientists (Doran and Safley, 1998). This is essential because the land managers are effectively going to be making the majority of the decisions and therefore need to understand and be able to utilise these indicators. It should also be noted that although individually the indicators provide little information about a specific soil function, collectively they provide a useful indication of the soil's condition or quality.

There have been a number of attempts to generate a minimum data set for soil quality indicators, that provides the core measurements needed for the evaluation of the chemical, physical and biological properties of the soil. Table 2.1 clearly outlines the minimum data set proposed by (Larson and Pierce, 1991, Doran and Parkin, 1994), and adapted by (Seybold *et al.*, 1998).

Although this is an extensive list there are still some additional indicators that merit being included, such as soil faunal numbers, (especially earthworm numbers) which can clearly be used as indicators of changes within the soil (Pankhurst, 1998). Aggregate stability is another important property that is not included but which changes rapidly in response to changes in soil management (Haynes and Beare, 1996).

There are also other types of indicators such as descriptive and production indicators (Doran and Safley, 1998), but these types of indicators tend to be subjective and are therefore of limited use. They can however be more useful on a farm or field scale, but a clear understanding of the flaws of these indicators is required. Crop yield (grain or biomass production), plant vigour, rooting pattern and other aspects of plant growth can certainly be important indicators since they provide information on the ability of the soil to sustain plant productivity through the interaction of many soil properties (Haynes, personal communication, 2000).

Monitoring soil quality trends requires establishing baseline values for the various indicators, and measuring changes in those indicators over time (Seybold *et al.*, 1998), the net effect on the management practice and climate can then be established and the appropriate management decisions made to ensure the maintenance or improvement of the soil quality.

Table 2.1 A proposed minimum data set of physical, chemical and biological indicators for screening the quality of soils (Seybold *et al.*, 1998).

Indicators	Relationship to soil condition and function: rationale as a priority measurement
	Physical
Texture	Retention and transport of water and chemicals; modeling use, soil erosion and variability estimate
Depth of soil and rooting	Estimate of productivity potential and erosion; normalizes landscape & geographic variability
Infiltration and bulk density	Potential for leaching, productivity, and erosivity; bulk density: SBD needed to adjust analyses to volumetric basis
Water holding capacity	Related to water retention, transport, and erosivity; available H_2O; calculate from SBD, texture, and OM
	Chemical
Soil organic matter (OM)	Defines soil fertility, stability, and erosion extent; matter (OM); use in process models and for site normalization
pH	Defines biological and chemical activity thresholds; essential to process modeling
Electrical conductivity	Defines plant and microbial activity thresholds; presently lacking in most process models
Extractable N, P, and K	Plant available nutrients and potential for N loss; productivity and environmental quality indicators
	Biological
Microbial biomass C and N	Microbial catalytic potential and repository for C and N; modeling: early warning of management effects on OM
Potentially mineralizable N	Soil productivity and N supplying potential; mineralizable N; process modeling (surrogate indicator of biomass)
Soil respiration	Microbial activity measure (in some cases plants); process modeling: estimate of biomass activity

Note: The abbreviation (SBD) is used in place of soil bulk density in the above table.

2.2.3 The importance of soil quality

Although soil quality cannot be measured directly, it serves as an umbrella concept for examining and integrating relationships and functions among various biological, chemical and physical parameters that are measured and important for sustainable agricultural and environmental systems (Karlen *et al.*, 1997). The maintenance and improvement of soil quality are essential for the sustainability of agricultural productivity. This is especially in today's agricultural systems where technological advances and increased inputs, can compensate and overshadow losses in soil quality due to bad management practices and therefore result in suitable yields, still being attained (Doran and Safley, 1998). These technological advances and increased inputs, such as chemical fertilizers and pesticides can also have unfavourable consequences on environmental quality.

The attainment of suitable yields can result in land users having a false sense of security about the sustainability of the management practices being employed. This can lead to further misuse and degradation of the soil resource. The concept of soil quality provides a basis on which to compare the effects of various management practices. It therefore has a place in today's agricultural systems, but the time and nature of sampling must be noted so that suitable comparisons can be made and the most appropriate management practices implemented. The monitoring of soil quality is already being carried out by environmental protection agencies in many parts of the world.

2.3 CENTRAL ROLE OF ORGANIC MATTER IN SOIL QUALITY

2.3.1 The central importance of soil organic matter

Soil organic matter is a key attribute to soil quality (Doran and Parkin, 1994; Haynes, 1997). It is important to recognise that the soil organic matter includes a number of fractions such as the light fraction, microbial biomass, water soluble organics and humus (Stevenson, 1994; Seybold *et al.*, 1998), and that soil organic carbon or soil organic matter is perhaps the single most important indicator of soil quality and productivity (Larson and Pierce, 1991; Cannell and Hawes, 1994; Gregorich *et al.*, 1994). There are various unfavourable consequences associated with a decrease in soil organic matter and these factors can have far reaching consequences in terms of the soil's physical, chemical and biological properties.

Although the soil organic carbon levels are one of the most important soil quality indicators the short term changes in soil organic C are difficult to quantify because of the large background organic C pool (Haynes, 1999a). The microbial biomass is composed of the living component of the soil and has a high turnover rate and responds rapidly to changes in C availability (Haynes, 1997). For this reason the microbial biomass C and N measurements provide foresight and are used as indicators of soil organic C and N contents. The use of the microbial biomass is particularly useful where changes in organic matter are expected, for example in the evaluation of tillage effects.

Some of the major reasons why soil organic matter is so important, are that it provides a sink for nutrients, it provides a substrate for microbial, and faunal activity, protects soil enzymes and is vital in the process of aggregation. Soil organic matter is essential for the functioning of the soil as a whole, and changes in soil organic matter provide the primary measure for determining which direction current management practices are headed (Gregorich *et al.*, 1994; Karlen and Cambardella, 1996).

The presence of soil organic matter is essential and extremely useful and it can be thought of as a 'buffer' which absorbs or reduces the ill effects of bad management practices or unfavourable occurrences on soil function. The way in which management practices effect soil organic matter content is usually through the rate and/or type of organic matter input and the rate of it's decomposition. Because of the importance of organic matter, management practices need to conserve and protect the soil organic matter levels. Although soil organic matter content varies naturally between locations and soils, (due to environmental conditions such as; temperature, water content, pH, aeration and soil texture), there is now a great concern regarding the decline in soil organic matter contents due to anthropogenic disturbances (Seybold *et al.*, 1999).

2.3.2 How organic matter effects the soil physical, chemical and biological properties

With respect to the evaluation of soil quality the interrelationship between the physical, chemical and biological properties is important. This interrelationship is largely dependent on a common factor; that is, the soil organic matter content. Table 2.2 gives an overview of some of the effects of soil organic matter (humus) on the soil.

Soil organic matter plays a fundamental role in the process of aggregation, (Haynes and Beare, 1996), which is essential in the development of soil structure. This effect on soil structure influences other important soil physical processes and properties, such as, the water holding capacity, the infiltration rate, aeration, the hydraulic conductivity, the extent of aggregation and the soil bulk density (Haynes and Williams, 1993). Soil organic matter has a profound effect on the structure of many soils and when organic matter is lost they tend to become harder, more compact and cloddy (Haynes, 1997).

The ways in which the chemical properties of the soil are effected by the soil organic matter content are usually through effects on the soil nutrient supply. Organic matter serves to increase the cation exchange capacity of the soil (Stevenson, 1994), and therefore usually results in the soil having a capacity to store and supply exchangeable cations. Organic matter also provides a source of mineralizable nitrogen, phosphorous and sulphur, as well as various other nutrients (Haynes, 1997).

The soil organic matter content greatly effects soil biological properties, because it provides the substrate for microbial and some faunal activity and it can also protect the soil enzymes. An increase in organic matter will stimulate an associated increase in soil microbial and faunal activity, and this can have a positive effect on soil physical properties such as aggregation and porosity. Indeed soil organic matter content and soil biological activity are intimately linked with soil aggregation and soil structural conditions (Haynes and Naidu, 1997).

From the above discussion it is evident that the soil organic matter content is vitally important to the physical, chemical and biological soil properties. Thus managing soil organic matter content is central to managing soil quality. In relation to soil degradation under annual pastures, the loss of soil induced by soil organic matter depletion is likely to be of particular importance. For this reason, the role of organic matter in aggregation and soil structure is reviewed.

Table 2.2 General properties of humus and associated effects in the soil (Stevenson, 1994).

Property	Remarks	Effect on soil
Color	The typical dark color of many soils is caused by organic matter	May facilitate warming
Water retention	Organic matter can hold up to 20 times its weight in water	Helps prevent drying and shrinking. Improves moisture-retaining properties of sandy soils
Combination with clay minerals	Cements soil particles into structural units called aggregates	Permits exchange of gases Stablizes structure Increases permeability
Chelation	Forms stable complexes with Cu^{2+}, Mn^{2+}, Zn^{2+}, and other polyvalent cations	Enhances availability of micronutrients to higher plants
Solubility in water	Insolubility of organic matter is due to its association with clay. Also, salts of divalent and trivalent cations with organic matter are insoluble.	Little organic matter is lost by leaching
Buffer action	Exhibits buffering in slightly acid, neutral, and alkaline ranges	Helps to maintain a uniform reaction in the soil
Cation exchange	Total acidities of isolated fractions of humus range from 300 to 1400 cmoles/kg	Increases cation exchange exchange capacity (CEC) of the soil. From 20 to 70% of the CEC of many soils (e.g., Mollisols) is caused by organic matter
Mineralization	Decomposition of organic matter yields CO_2, NH_4^+, NO_3^-, PO_4^{3-}, and SO_4^{2-}	Source of nutrients for plant growth
Combines with xenobiotics	Affects bioactivity, persistence, and biodegradability of pesticides	Modifies application rate of pesticides for effective control

2.3.3 The process of aggregation and it's importance

Since soil organic matter is central to the formation of stable aggregates there is normally a close relationship between soil organic matter content and water stable aggregation in soils, (Chaney and Swift, 1984; Haynes and Naidu, 1997). To understand the process of soil structural formation, firstly an understanding of the processes of microaggregation and macroaggregation are required. The importance of aggregation should not be overlooked, because it forms the basis of the development of soil structure and porosity, which are essential attributes of soil quality and are vital in maintaining favourable conditions for plant growth (Haynes and Beare, 1996).

The process of aggregation occurs at two different scales (Haynes and Beare, 1996), that of microaggregates which involves the binding of particles <250 μm in diameter and that of macroaggregates, which involves the binding of particles which are >250 μm in diameter. Macroaggregates are formed through the combination of many microaggregates. The types of bonds involved at the two scales also differ, with those involved in the process of microaggregation tending to be stronger than those involved in the macroaggregation process. The two components of organic matter that are mainly responsible for the binding action involved in aggregation are humic substances and polysaccharides (Haynes and Beare, 1996).

Some controversy surrounds the relative importance of various processes involved in micro and macroaggregation, but generally the relative importance is soil and site specific(Reeves, 1997). Table 2.3 provides a general overview from which a suitable understanding of the various binding agents and their scale of activity can be generated.

Soil humic substances characteristically interact with the mineral component of the soil to form water-insoluble associations of widely differing chemical and biological stabilities (Schnitzer, 1986; Haynes and Beare, 1996). A positive correlation has also been found between the amount of humic acids in the soil and the degree of macroaggregate stability, and this further illustrates the importance of humic substances in the process of aggregation. The humic substances also make up a significant portion of the total organic C and N in soil (Anderson, 1979; Gregorich *et al.*, 1994); and will therefore also effect the nutrient availability to a degree.

Polysaccharides are the other major fraction of organic matter that is involved in aggregation. They represent a significant pool in the soil organic matter (5 - 20% of the total soil organic C), (Gregorich *et al.*, 1994). Polysaccharides are exuded into the rhizosphere from plant roots and are also exuded from fungi and bacteria (Haynes and Beare, 1996). Polysaccharides stabilise aggregates by the formation of organo-mineral bonds, which glue the particles together. Within the rhizosphere of pastoral systems, where large amounts of microbial polysaccharides are being continually produced, polysaccharide-mediated stability of macroaggregates may be of particular importance (Haynes and Beare, 1996); and be responsible for a substantial proportion of the binding that occurs. Although polysaccharides are involved in the process of aggregation at both scales, they tend to predominate at the macroaggregate scale (Rennie *et al.*,1963; Acton *et al.*, 1963; Haynes and Swift, 1990; Angers *et al.*, 1993b; Gregorich *et al.*, 1994). Figure 2.1 provides greater insight into the different scales of aggregation, as well as the various constituents involved in the formation of the different sized aggregates. This allows a greater understanding of the formation of aggregates and therefore of soil structure.

Table 2.3 Table showing the summary of the major binding and aggregating agents and their role in soils of warm humid climates (Haynes and Beare, 1996).

Aggregating agents	Aggregation process	Major scale of aggregation
Humic substances	Form strong bonds with soil mineral components	Basis of microaggregate formation
Polysaccharides	Act as gelatinous glueing agents Form organo-mineral associations	Involved in stabilization of both micro- and macroaggregates
Plant roots	Enmesh soil aggregates Exude polysaccharides	Agents of macroaggregate formation and short-term binding
Fungal hyphae	Enmesh soil aggregates Exude polysaccharides	Agents of macroaggregate formation and short-term binding
Earthworms	Mix organic matter and clay colloids together Mix decaying detritus with the bulk soil	Agents of macroaggregate formation

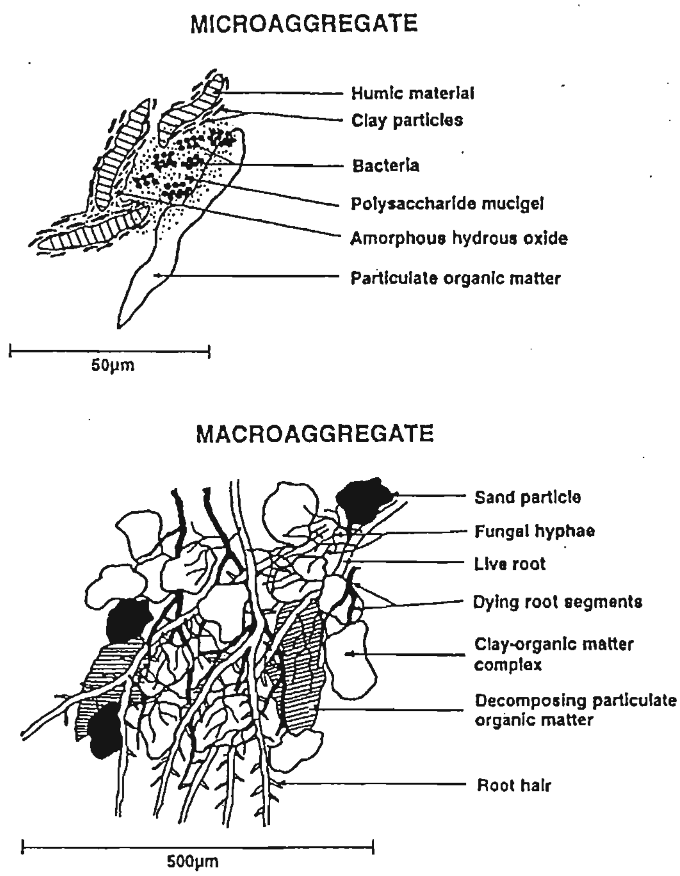


Figure 2.1 Figure showing the schematic diagram of the structure of a micro-and a macroaggregate (Haynes and Beare, 1996).

The development of microaggregates occurs when mainly humic material combines with clay particles and other mineral constituents. These microaggregates can be seen as the primary components of soil structure since they bind together and with other particles such as sand and organic matter to form macroaggregates. There are various other processes in the soil that assist in the formation of macroaggregates and they include, the wetting and drying cycles of the soil, the enmeshing effect of plant by roots and fungal hyphae and the activity of the soil faunal component, especially earthworms (Haynes and Beare, 1996). Since humic molecules and polysaccharides are principally products of microbial metabolism it follows that microaggregate formation occurs mainly at sites in the soil of high microbial activity (Haynes and Beare, 1996).

Hence soils with higher organic matter contents will have an associated higher microbial activity and therefore a better or more developed micro-and macroaggregation.

The mechanism by which the organic matter becomes bound into the soil aggregates has a direct effect on the accessibility of the organic matter to microbial degradation. The organic matter found within the microaggregates, which is mainly humic material, is strongly bonded to clay particles and not easily degraded (Haynes and Beare, 1996). When a soil is disturbed, for example by cultivation, it results in the breaking up of the macroaggregates and the decomposition of organic matter involved in macroaggregation (Karlen *et al.*, 1994). This previously inaccessible organic matter is exposed to microbial attack and is decomposed, resulting in a decrease in macroaggregation and a breakdown in soil structure(Haynes, 1997).

The addition of organic materials to soils has a positive effect on aggregation (Haynes and Naidu, 1997); both directly because of the addition of humic material and polysaccharides and indirectly because of the stimulation of microbial and faunal activity. The type of organic matter and the degree of decomposition is important because it effects the associated aggregation processes. The addition of an easily decomposable organic source results in a short, rapid increase in aggregate stability during the period while microbial activity is stimulated (Haynes and Naidu, 1997). By contrast the addition of a well decomposed organic matter source will result in a gradual increase in aggregate stability because of the addition of already humified material (Haynes and Naidu, 1997). Although both these effects are favourable in terms of soil quality they can effect the overall soil physical properties differently and over a different time scale.

2.3.4 Soil structure and it's importance

Soil structure can be described as the architecture of the soil. It describes the size, shape and stability of the solid soil material and the size, shape and continuity of the spaces (pores) between the soil solids (Haynes, 1995). The stability of the soil structure, or soil strength, is a vitally important property because it determines the soil's ability to resist disturbances without collapsing or being deformed, i.e. maintain its pore characteristics (Lal, 1993). Soil structure is essential because it allows soil physical processes, such a drainage, infiltration, hydraulic conductivity and aeration to occur. These are crucial processes for plant growth. It also allows the soil to resist erosive forces from water and wind, which can cause severe damage through loss of topsoil. The soil structure is a variable which is greatly dependent on the quantity and quality of soil organic matter and can therefore be affected by any management practice which effects the soil organic matter content.

When soil structural breakdown occurs, it results in the soil losing it's ability to withstand disturbances and this usually occurs due to a reduction in the amount of soil organic matter. There are various consequences associated with structural breakdown, such as, reduced infiltration rate, the occurrence of surface crusting and compaction, reduced drainage, aeration and hydraulic conductivity, reduced crop emergence (Haynes, 1995). This in turn can also effect some of the soil chemical and biological properties unfavourably. During structural breakdown the small particles or microaggregates split off from the macroaggregates due to the reduction in the strength of the bonds holding the macroaggregates together (Karlen *et al.*, 1994).

2.4 PERMANENT VERSUS ANNUAL / ARABLE PASTORAL SYSTEMS

2.4.1 Permanent pastoral systems

Pastoral systems exist as part of a soil, plant, animal system (Haynes and Williams, 1993), and this is a complex ecosystem. The soil component will be evaluated in terms of the effects of permanent or arable pasture management on the soil chemical, physical and biological properties and processes. Under permanent pasture soil quality improves because of the increased soil organic matter returns due to a typically dense ramified root system and the high turn over rate of the plant and root material (Haynes, 1995). It was shown by (Francis *et al.*, 1999), that after six years under pasture, several soil quality attributes such as organic matter content, nitrogen fertility, aggregate stability and microbial biomass had improved compared to soils cropped annually.

It has been recorded that in temperate agricultural soils, organic carbon content often ranges from 3 to 6 % in pastoral soils but is usually in the range of 1 to 2 % or even lower under continuos arable management (Haynes and Beare, 1996). When arable land is converted to permanent pasture there is typically an appreciable increase in soil organic matter content (Haynes and Francis, 1993). The rate of organic matter accumulation and the time taken to reach equilibrium, where organic matter additions are balanced by mineralisation and loss, varies considerably depending on soil type, climate and management (Haynes and Beare, 1996).

Where native vegetation is replaced by improved pasture there can also be an appreciable increase in organic matter content because the pasture is fertilized and often irrigated so that plant dry matter production (and therefore organic matter returns) are significantly increased (Karlen and Cambardella, 1996). Organic matter inputs are highest under pasture near the soil surface, from the turnover of roots and inputs from above ground residues, and this decreases with depth. As a result, soil organic matter content and related microbial activities are characteristically highest near the soil surface and decrease markedly with depth (Haynes and Beare, 1996). This results in an associated decrease in organic C with depth, which can be seen in Figure 2.2. The effect of tillage on organic C distribution is also evident from the figure, with conventional tillage having a fairly even distribution and zero tillage having a noticeable accumulation at the surface.

A large input of below ground particulate organic matter, due to turnover of grass roots and the absence of tillage are thought to be the two key factors leading to sequestration of organic carbon under permanent pasture (Paustian *et al.*, 1997). The negative effects that tillage has on soil organic matter content is discussed in detail in section 2.4.2.

Another important factor is the recycling of organic matter and nutrients mediated by the grazing animal (see section 2.5.3). Soil organic matter content was shown by During and Weeda,(1973), Haynes and Williams, (1993), to be significantly increased below dung pats. Large amounts of organic matter are deposited in dung patches (e.g. equivalent to 20 - 50 Mg ha^{-1}), (During and Weeda, 1973; Haynes and Williams, 1993); and dung deposition is believed to play a major role in the buildup of organic matter that occurs under improved pastures (Haynes and Williams, 1993).

Within permanent pastures, there is still some form of cultivation that occurs sporadically during pasture renovation and/or resowing. This is usually in the form of direct drilling or some other minimal tillage practice(Anonymous, 1986). Such practices are favourable to the maintenance of soil organic matter levels, because they create minimum disturbance.

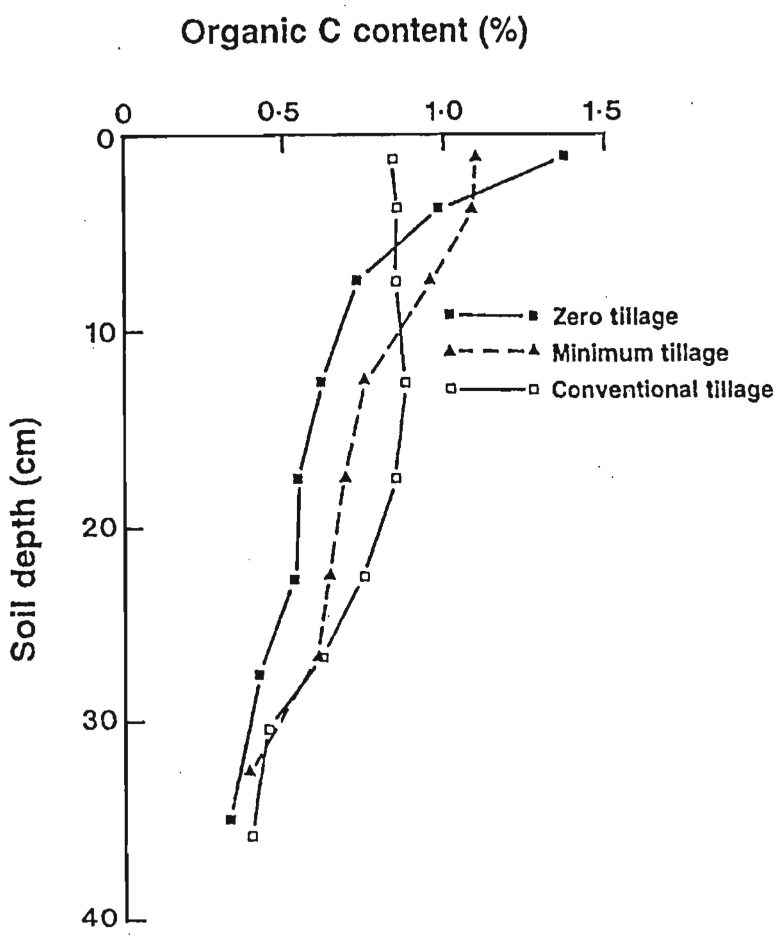


Figure 2.2 Profiles of organic C in a soil after 10 years of zero tillage, minimum tillage, conventional ploughing or continuous grass (Redrawn from Douglas *et al.*, 1986; by Haynes and Beare, 1996).

2.4.1.1 Chemical characteristics

As already noted, soil organic matter status is characteristically high under permanent pasture. The importance of organic matter in soil nutrient status through, for example, its effects on N availability and cation exchange capacity were outlined in section 2.3. Soil fertility is usually high under improved pasture (Haynes, 1999b), but this is obviously highly dependent on fertilizer rates that have been applied. The lack of cultivation tends to result in an accumulation of nutrients in the surface layers of the soil. This is particularly marked for immobile nutrients such as P, Cu and Zn, which tend to be concentrated in the top few centimetres of the soil and decrease greatly with depth (Blevins and Frye, 1993). Because of the lack of soil mixing in no-till systems the addition of soil amendments, such as fertilizer, lime, herbicides or insecticides often has a reduced effect (Cannell and Hawes, 1994), since they are limited to the surface layer. Overall the nutrient, pH and amendment distribution within a no-till profile will be different from that of a conventionally tilled soil.

Under permanent pastures the returns from grazing animals are vitally important and the dung and urine patches are areas of pasture where large amounts of nutrients are returned and therefore concentrated, (see section 2.5.3). The soil nutrient status of these areas differs markedly from the surrounding areas and as a result, excretal patch areas contribute greatly to spatial variability in extractable soil nutrient concentrations across grazed pastures (Haynes and Williams, 1993). This inherent spatial variability in soil nutrient status under pastoral farming makes sampling strategies for soil testing of critical importance and some have suggested it makes fertilizer recommendations based predominantly on soil test values of questionable value (Haynes and Williams, 1993).

The accumulation of soil organic matter in the surface layers increases the soil's cation exchange capacity and results in an increase in the H^+ ion saturation of the exchange complex (Vitosh *et al.*, 1997). This can therefore lead to a decrease in soil pH. The decomposition of organic material results in the production of organic acids which also have an acidifying effect, especially in pastures which contain a significant component of legumes (Blevins and Frye, 1993). This is because actively N_2 fixing legumes generally acidify their rhizosphere due to the excretion of H^+ in response to excess cation-over-anion uptake (Anonymous, 1986).

Although this acidification process is usually slow, (it may take 25 to 50 years for the pH to decrease by one unit), (Haynes and Williams, 1993), it can have serious implications for pastoral production through aluminium and manganese toxicities limiting growth (Haynes and Naidu, 1997). Grasses are however usually fairly tolerant to acidity and the overall effect of pasture is still generally favourable in terms of soil quality (Anonymous, 1986).

2.4.1.2 Physical characteristics

Generally the soil physical properties are positively effected by the implementation of a permanent pastoral system (Haynes, 1995), and the physical characteristics that change under permanent pasture do so mainly because of the associated increase in organic matter content. The changes that commonly occur include an increase in the aggregate stability and an increase in the mean size of the aggregates (Cannell and Hawes, 1994). This can be partially attributed to the high soil organic matter content and thus the binding actions of humic substances as explained in section 2.3.3 and 2.3.4. Nevertheless, it has been shown that aggregate stability can increase appreciably when arable land is converted to pasture before any significant increases in total soil organic matter content can be detected (Haynes and Swift, 1990; Haynes *et al.*, 1991; Haynes and Beare, 1996). The dense, much ramified, fine root system of grasses has an enmeshing effect, as does the mycorrhizal fungal hyphae associated with the root (Tisdal and Oades, 1979). The dense root system also supports a larger microbial population in the rhizosphere which produces polysaccharide gums that also help bind the soil particles together (Roberson *et al.*, 1991).

Soil porosity is another physical characteristic that is positively effected by the presence of a permanent pasture (Haynes and Williams, 1993). The total porosity and the air-filled porosity at field capacity are improved because of the formation of extensive root channels, the increase in the number of earthworm channels and the increase in the cracking of the soil due to a greater water use and an associated increase in the wetting and drying cycles of the soil. With the improvement in soil macro porosity an associated increase in the infiltration rate, and soil hydraulic conductivity can occur (Blevins and Frye 1993). The soil bulk density is also typically decreased under permanent pastoral systems (Haynes, 1995), because of the increase in soil organic matter content and the increased porosity. The soil water retention is also improved because of the increased organic matter content (Stevenson, 1994).

Although the implementation of a permanent pastoral system has many benefits in terms of soil physical condition, some negative effects can occur. Problems such as treading damage and compaction induced by the hooves of livestock can easily occur within permanent pastoral systems (Haynes, 1995), (see section 2.5.2).

2.4.1.3 Biological characteristics

The overall biological activity of the soil generally increases when arable soils are converted to grazed pasture (Russell, 1986; Haynes and Williams, 1993). Understandably, permanent pastures have many favourable effects on the soil biological properties and the main mechanism through which these biological properties are effected is by the increase in the soil organic matter content (Francis *et al.*, 1999).

Associated with the high content of soil organic matter and dense mass of pasture roots is a large microbial biomass (Haynes and Williams, 1993). This is typical of a pasture rhizosphere and is favourable because it provides a large labile pool of nutrients (Haynes and Williams, 1993), and accounts for 1 - 3 % and 2 - 6 % of soil organic C and total N respectively (Stevenson, 1994). Microbial biomass is also important because it serves as an agent of decomposition of plant residues (Haynes, 1997). The microbial biomass is in the region of 1200 μg C g $^{-1}$ under improved pasture (see Figure 2.4), which commonly represents 150 - 225 kg N ha $^{-1}$ and 10 - 60 kg P ha $^{-1}$ (Haynes and Williams, 1993), which can be released when the microbial population dies, and is therefore an important source of nutrients. Although some seasonal patterns have been observed in the levels of nutrients present in the microbial biomass under pasture, it is likely that the magnitude of the various nutrient fluxes that operate through the large labile biomass pool are of greatest significance to pasture fertility (Haynes and Williams, 1993). The soil microbial biomass also plays a vital role in the maintenance of soil structure (Lynch and Bragg, 1985; Haynes, 1997).

Under permanent pasture the activity of soil enzymes are also typically increased, and this reflects high soil organic matter content and high microbial activity (Haynes and Williams, 1993). The activities of the enzymes involved in N, P and S cycling were all highly correlated with organic matter content (Haynes, 1999b), and are therefore typically high under permanent pastoral systems (Haynes, 1997). This reflects a high rate of turnover of these nutrients in the soil (Baligar and Wright, 1991; Baligar *et al.*, 1991; Gregorich *et al.*, 1994). As expected higher enzyme activity is found under improved pasture than unimproved wilderness areas, and under productive pastures than under unfertilized pastures (Haynes and Williams, 1993).

The soil conditions under permanent pasture are particularly favourable for the soil faunal component, especially earthworms because of the increased organic matter and the lack of soil disturbance (Berry, 1994). Pasture improvement, or increased time under pasture has been shown to result in an increase in earthworm numbers (Sears and Evans, 1953; Suckling, 1975; Haynes and Williams, 1993), and the weight of earthworms per hectare is closely correlated with pasture production and stock carrying capacity (Fraser *et al.*, 1992; Fraser, 1994), and is therefore effected by any management practice that effects pasture production. Earthworm numbers in productive temperate grasslands vary from 100 - 1000 m^{-2} (Curry, 1987; Fraser, 1994), and the application of N fertilizer to pastures has a favourable effect on their numbers (Haynes and Williams, 1993). Haynes *et al.* (1991) observed that populations averaged about 800 - 900 earthworms m^{-2} under long term pasture and less than 200 m^{-2} under long term arable pasture (Fraser, 1994), (see Table 2.4).

The role of earthworms in cycling nutrients under pasture is substantial, and they perform many functions within the soil which are important in terms of soil quality, for example, they improve aggregation, porosity, infiltration, bulk density, nutrient cycling, aeration, root penetration and microbial activity (Pankhurst, 1998). They ingest soil and organic litter and it is mixed in their gut. This mixing facilitates contact between the mineral and the organic components thus promoting macroaggregation. Earthworms also help improve the pore continuity, water infiltration, hydraulic conductivity and bulk density through their burrowing actions (Berry, 1994), as well as increase the rates of nutrient cycling within the soil (Fraser, 1994). Indeed, the availability of N and P in casts is higher than that of uningested soil because mineralisation of organic matter is promoted during gut transit (Blair *et al.*, 1995; Haynes, 1997).

2.4.2 Annual / arable / pastoral systems

An annual or arable pastoral system is sown or planted every year. This involves the cultivation and preparation of the land, which usually includes primary tillage such as the use of a mouldboard plough and then secondary tillage (Karlen *et al.*, 1994), which may involve harrowing, discing or the use of a rotavator to prepare a suitable seedbed. All of these practices cause disturbances to the soil and are therefore potentially unfavourable. For example, the soil aggregates are pulverised and the previously protected organic matter is then exposed and mineralised by the soil microbes (Haynes and Beare, 1996). The mixing of the soil introduces more oxygen into the soil and increases the activity of aerobic microorganisms (Cannell and Hawes, 1994). This mixing effect also increases the surface area of the substrate available to the microbial population and therefore further increases the degree of mineralisation. Because this occurs regularly in arable systems, these disturbances typically result in a net loss of soil organic matter. Tillage has accordingly been described as effecting the soil C balance in two fundamental ways; through physical disturbance and mixing of the soil and through controlling the incorporation and distribution of plant residues into the soil (Paustian *et al.*, 1997).

Other negative effects of tillage include; a decrease in aggregation and aggregate stability, the disruption in the continuity of macropores, the reduction in soil biodiversity and macrofauna activity (e.g. earthworms and termites) and an increase in water and wind erosion (Paustian *et al.*, 1997). These alterations change the balance and cycles of water, carbon and principal nutrients (Lal,1993), and can therefore have serious implications in terms of soil sustainability. This is however a generalisation and the effects of tillage are to a large degree site specific. The degree of soil disturbance caused by tillage is difficult to define and quantify but a commonly used measure is aggregate stability (Paustian *et al.*, 1997). Figure 2.3 shows the effects of various management practices on the soil organic carbon content and helps put into perspective the scale of difference between permanent and arable pastures.

The Rothamsted experiments are long term experiments and the results are as expected, with the long term pastures having the highest organic C content and the long term arable having the lowest. A characteristic increase in organic C is also shown in the conversion of arable to pasture, with the converse being shown from pasture to arable. Aggregate stability follows a similar trend.

The most dramatic effects of agricultural land use on soil C are associated with the initial cultivation of native soils, the C in the effected layer decreases rapidly and eventually stabilises after many years (Paustian *et al.*, 1997). Rasmussen *et al.* (1989), reported that when virgin eastern Oregon soils were cultivated, many lost more than 25 % of their organic matter in the first 20 years and 35 - 40 % in 60 years (Karlen and Cambardella, 1996).

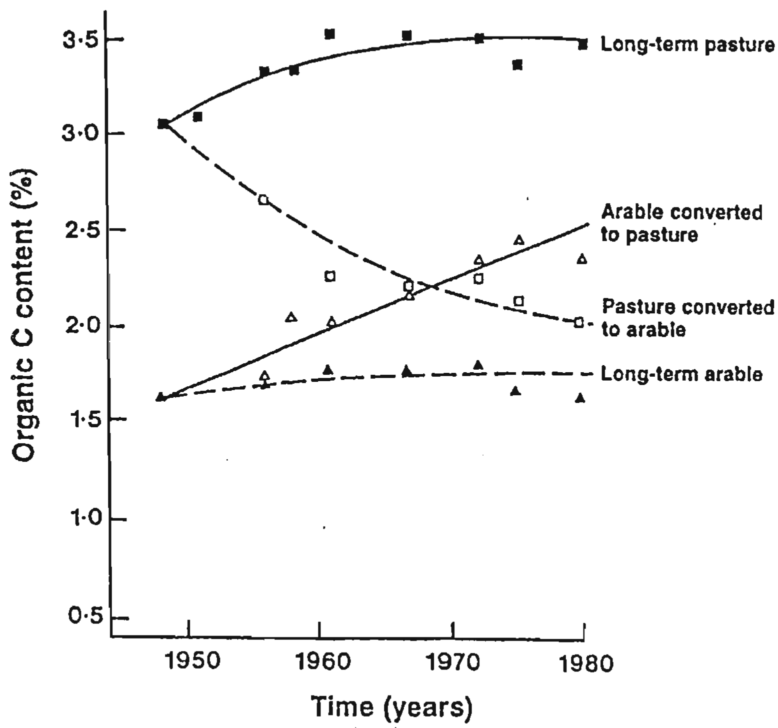


Figure 2.3 Organic C content of soils from the Rothamsted ley-arable experiment. Treatments consist of long term grassland, long term grassland soil converted to arable and long term arable, and long term arable soil converted to grassland. (Redrawn from Johnston, 1986; by Haynes and Beare, 1996).

In arable systems, cultivation induced degradation of soil organic matter is not the only factor leading to a decrease in organic matter content. The inputs of organic material are generally much lower than those under natural vegetation. This is attributable to a relatively wide spacing of plants, removal of harvested organic material (e.g., grain) and removal or burning of crop residues (Paustian *et al.*, 1997). The loss of C also depends on the type and length of cultivation, soil type and climate (Paustian *et al.*, 1997). The influence of crop rotation on organic matter content under arable farming is generally closely related to the quantity of crop residue returned to the soil during the rotation (Karlen and Cambardella, 1996). The distribution of C inputs may also be altered under arable management, for example, a lower proportion of C is added below ground in annual crops versus perennial grasslands (Anderson and Coleman, 1985; Paustian *et al.*, 1997).

Fallowing is a particularly detrimental practice since organic residue inputs are insignificant and the soil is often tilled thus promoting organic matter degradation. Decreases in organic C with increased frequency of fallow within the rotation have been well documented (Drover, 1956; Dormaar and Pittman, 1980; Janzen, 1987; Rasmussen *et al.*,1989; Campbell and Zentner, 1993; Paustian *et al.*, 1997). An associated decrease in aggregate stability is also common (Sauerbeck, 1982; Tisdall and Oades, 1982; Johnston, 1986; Haynes and Beare, 1996). Fertilizer additions tend to increase soil organic matter content because they promote crop growth and therefore increase returns of organic residues as roots and stubble to the soil (Haynes and Naidu, 1997), (see section 2.5.1).

The intensity with which the soil is cultivated can affect both the total amount of soil organic C present and its distribution with soil depth. Residue inputs are generally concentrated at the soil surface under zero tillage so that organic C and N contents are enhanced in the surface soil layers (Paustian *et al.*, 1997), this can give a misleading impression for soil testing. By contrast under conventional tillage organic matter is more or less evenly distributed to the depth of cultivation (Haynes and Beare, 1996). In a review of a number of long term field trials, Paustian *et al.* (1997), also showed that in comparison with conventional tillage, soil organic C retention is typically enhanced under zero tillage.

The use of pastures in rotation with arable crops can contribute to the maintenance of soil organic matter content (Johnston, 1986; Paustian *et al.*, 1997). This system, known as ley-arable farming, consists of pasture leys (3 - 6 years) being alternated with 3 - 4 years of arable crops. Increases in organic C content under ley-arable cropping compared with continuous arable production have been reported in a number of European studies (Kooistra *et al.*,1989; Tyson *et al.*, 1990; Paustian *et al.*, 1990; Paustian *et al.*, 1997). Clement and Williams, (1964), reported an average increase of 15 % in total soil C after 4 years of pasture whereas C decreased in annually cropped treatments (Paustian *et al.*, 1997). Overall though, such rotations do not always result in spectacular increases in organic matter (Haynes and Beare, 1996), since following the pasture phase the soil is typically conventionally cultivated therefore promoting degradation of the accumulated organic matter.

The effects of annual pastures which are conventionally cultivated and resown each year (as is common practice in the South African dairy industry), on soil organic matter levels is unknown. Since organic matter inputs under grass are typically high in comparison with most arable crops, one would expect soil organic matter accumulation to be greater under annual pasture than annual arable crops. However in a 5-year study comparing annual pasture production with annual barley production Haynes (1999b), found that there was no significant accumulation of total soil organic matter under annual pasture where conventional tillage was practised in both systems. This indicates the highly degradative effect that annual tillage had on both systems. Where the pasture was resown by direct drilling and tillage was therefore excluded from the annual pasture system, there was a relative accumulation of organic C in comparison with conventionally cultivated barley (Haynes, 1999b). A similar trend can be seen in Figure 2.4, where the annual grass zero tillage (ZT) has a higher microbial biomass C content than the annual grass conventionally tilled (CT), this indicates that over a longer experimental period that a significant difference would develop between the organic C contents in the two treatments. These two tillage practices are on opposite ends of the tillage spectrum and a difference in soil C response is therefore expected (Paustian *et al.*, 1997). The difference in organic C content between permanent and annual pastures is also evident.

The most noticeable difference is the magnitude of the difference between the long term pasture (63 g C kg^{-1}) and the long term arable (29 g C kg^{-1}),treatments. Although there is no significant difference in the organic C between the conventionally and the zero tilled soils, there is in the microbial biomass C. This indicates that a possible change in organic C will occur if the current management practices are continued and illustrates the use of microbial biomass C as a soil quality indicator.

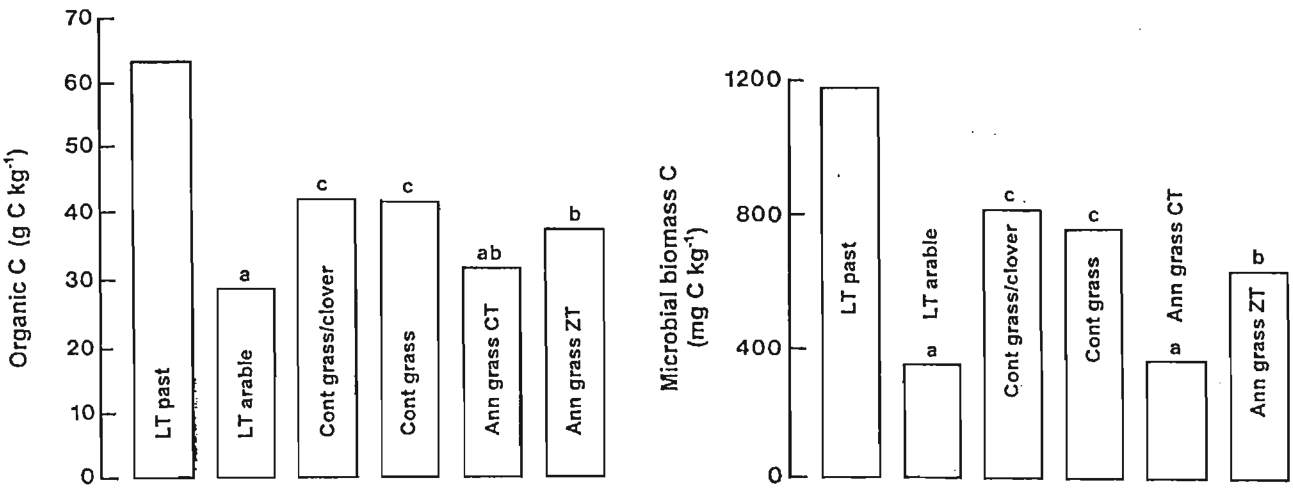


Figure 2.4 Quantities of organic C and microbial biomass C in 0 - 2.5 cm soil layer at various study sites. Means associated with the same letter are not significantly different ($P < 0.05$). (Haynes, 1999a).

Soil degradation by water and wind erosion and depletion of organic matter, with related consequences, including loss of nutrients, in many circumstances are among the main factors affecting the quantity and quality of land and thus the long term sustainability of arable agriculture (Cannell and Hawes, 1994). Tillage practices generally promote erosion and can therefore be considered unfavourable in terms of soil quality.

2.4.2.1 Chemical characteristics

Arable soils are exposed to various tillage practices and this results in both mixing of the soil to the depth of cultivation and degradation of the soil organic matter content (Karlen *et al.*, 1994). Both factors influence soil fertility and the loss of soil organic matter means that arable soils characteristically have a low ability to supply N via mineralisation (Haynes, 1997). This necessitates the use of high rates of N fertilizer in most arable systems (Karlen and Cambardella, 1996). The mixing of the soil has both positive and negative effects. For example, tillage means that lime and fertilizers are incorporated into the plough layer and thus into the soil volume where most of the crop roots are concentrated (Cannell and Hawes, 1994). As a result the chemical characteristics are usually fairly uniform within the plough layer (Cannell and Hawes, 1994; Karlen and Cambardella, 1996).

The incorporation of surface applied amendments can also be important from the viewpoint of minimising gaseous losses (e.g. NH_3 volatilisation) (Karlen and Cambardella, 1996). By contrast mixing nutrients that are rapidly fixed by soil colloids (e.g. phosphate) into the plough layer via cultivation can increase their fixation and decrease their availability (Cannell and Hawes, 1994). For this reason fertilizer P is often banded in the planting rows under arable agriculture (Karlen and Cambardella, 1996).

Soil acidification can be a particular problem under arable agriculture because of the high rates of fertilizer N applied (Blevins and Frye, 1993). Nitrification of NH_4^+ originating from applied fertilizer result in the release of H^+ ions into the soil system (Blevins and Frye, 1993). Where there is appreciable $N0_3^-$ leaching, the nitrate moves downward with Ca^{2+} and Mg^{2+} (normally the dominant exchangeable cations present) as counterions and the H^+ ions are effectively left in the plough layer. For this reason, lime is routinely incorporated into arable soils to maintain an adequate soil pH.

2.4.2.2 Physical characteristics

The effects of tillage on soil structure are not all unfavourable. One benefit of a tillage practice is that it provides a loosening action that helps to maintain or improve soil porosity (Haynes, 1995). This is particularly beneficial in soils that are compacted. However if tillage is incorrectly used it can set in motion a wide range of degradative processes including deterioration in soil structure, and accelerated erosion (Lal, 1993).

The soil physical properties of arable soils are generally of concern because of the structural breakdown that can occur due to the reduction in soil organic matter content. When a pasture is converted to arable cultivation the major source of organic matter that is mineralised is that involved in macroaggregation (Haynes and Beare, 1996). The reduction in organic matter and loss of macroaggregate stability leaves the soil more susceptible to physical degradation including, compaction, slaking, slumping and hardsetting (Haynes, 1995). As a result there may be reductions in infiltration capacity, aeration, porosity, pore continuity, pore size distribution, root penetration and water holding capacity (Blevins and Frye, 1993).

Poor soil physical conditions can be a limiting factor to crop production on arable land. It can result in more passes of secondary tillage implements being required to produce a suitable seedbed (Haynes, 1995); and the production of a seedbed with a substantial proportion of very fine particles that are particularly susceptible to erosion by wind (Paustian *et al.*, 1997). They can also result in ponding of water at the soil surface, surface runoff and associated water erosion (Singleton and Addison, 1999), and surface capping with inhibition of seedling emergence and growth (Haynes, 1995).

Cultivation invariably affects soil structure and conversion from pasture to cultivated land yields substantial reductions in aggregate stability within a few years (Tisdall and Oades, 1982; Elliott, 1986; Angers *et al.*, 1992; Paustian *et al.*, 1997). Table 2.4 shows the influence of previous cropping history on aggregate stability, the reduction in aggregate stability and organic C with increasing time under arable can clearly be seen. The converse is true for increasing time under pasture.

Within an annual pasture grass roots will have similar positive effects on aggregate stability that they do in permanent pastures, since the enmeshing effect of fine grass roots and associated mycorrhizal hyphae and the production of polysaccharides by the rhizosphere microflora will still occur (Haynes and Francis, 1993).

Table 2.4 Influence of previous cropping history on aggregate stability, expressed as mean weight diameter (MWD, i.e. aggregate stability increases with increasing MWD); and percentage, the effect on earthworm numbers and organic C in a Lismore silt loam in New Zealand. Adapted from (Haynes *et al.*, 1991; Paustian *et al.*, 1997; Haynes, 1997).

Cropping history	Aggregate stability (MWD)	Aggregate stability (%)	Earthworm numbers (no.m^{-2})	Organic C (%)
10 year arable	1.0	18	130	2.0
4 year arable	1.2	22	260	2.4
1 year arable	1.3	23	380	2.4
1 year pasture	2.0	40	510	2.4
4 year pasture	2.5	62	760	2.5
10 year pasture	2.7	-	830	3.2

Note: Cropping histories for arable systems indicate years under annual cropping after coming out of pasture and conversely, for pastures, years in pasture after coming out of annual cropping.

2.4.2.3 Biological characteristics

Annual cultivation of soils results in a reduction of soil organic matter and continual soil disturbance (Karlen *et al.*, 1994), both of which are highly unfavourable to soil microbial and faunal populations and as a result there is a general decline in the biological activity (Seybold *et al.*, 1999). Tillage method (direct drilling versus conventional tillage), has a large effect on earthworm population size and composition, with populations being 1.5 - 3 times larger under direct drilling than conventional cultivation (Francis and Knight, 1993; Parmelee *et al.*, 1990; Fraser, 1994).

Reduced organic matter results in a reduced substrate for both the soil microbial and faunal activity (Haynes and Beare, 1996). A reduction in biodiversity is common within arable systems (Berry, 1994), and this is considered unfavourable. For example, most soil recovery mechanisms are biologically mediated (Seybold *et al.*, 1999), and biodiversity is therefore important. Soil enzyme activity is also adversely effected by annual pastures because of the decrease in the amount of available substrate.

The positive effects of an annual pasture are not as great as those from a permanent pasture, even though the rhizosphere effects are similar (Haynes and Francis, 1993). The reason for this is that there is an overall reduction in the amount of organic matter within an annual pastoral system (Haynes, 1999a), and therefore a reduction in aggregate stability, microbial biomass and faunal activity.

Several workers have shown that when crops are compared with respect to their ability to improve aggregate stability, the same sequence is found as that for root mass or root length density (Stone and Buttery, 1989; Perfect *et al.*, 1990; Haynes and Francis, 1993). Grass species characteristically produce a high ratio of below to above ground biomass and spread by tillering, resulting in a high root mass and length density (Haynes and Francis, 1993). In addition grass plants are normally sown at a relatively high density, compared with most other arable crops. As a result, in an arable situation they normally confer a higher aggregate stability on soils than other crops (Haynes and Francis, 1993); see Figure 2.5 (a). However the effect of short term grass leys in improving soil physical properties is often only transitory and not long lived (Grace *et al.*, 1994). This is because the pasture is ploughed in and this strongly promotes decomposition of any soil organic matter accumulated under the pasture. The grass roots and rhizosphere effects are rapidly lost following cultivation (Haynes and Beare, 1996). As a result aggregate stability rapidly decreases and so to do the other improved physical properties (Blevins and Frye, 1993). The positive effect of the rhizosphere on aggregate stability can be seen in Figure 2.5 where the comparison is shown between the rhizosphere and non-rhizosphere areas. The hot-water-extractable carbohydrate content is used as a measure of the soil's exocellular microbial polysaccharide, which are involved in aggregate stability (Haynes and Francis, 1993).

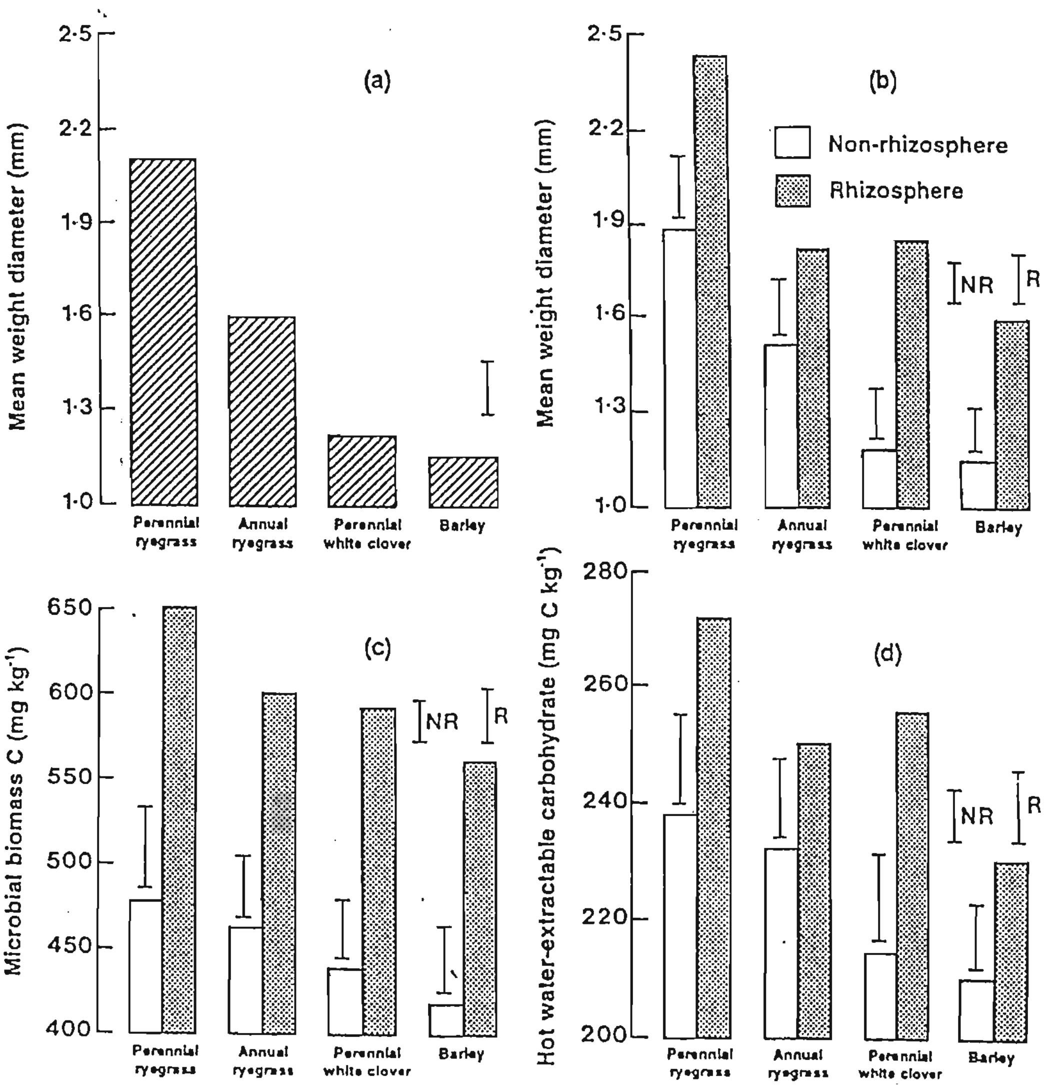


Figure 2.5 Mean weight diameter of whole plots (a) and mean weight diameter (b), microbial biomass C (c) and hot-water-extractable carbohydrate content (d) and non-rhizosphere (NR) soil after three growing seasons of four crop species. LSD (P< 0.05) for compaction between treatments and between rhizosphere and non-rhizosphere soil shown (Haynes and Francis, 1993).

2.5 THE EFFECTS OF OTHER MANAGEMENT PRACTICES

2.5.1 The effects of fertilizer, lime and manure applications

The effects of lime, fertilizer and manure applications on the soil organic matter content and physical properties have been recently reviewed (Haynes and Naidu, 1997). Fertilizer applications have greatly increased pasture production on many grassland soils that are inherently deficient in nutrients (Haynes and Williams, 1993). The requirement for fertilizer and lime is often high when pastures are first developed (Haynes and Williams, 1993). Large nutrient inputs are often required during the establishment stage and this can also be the case for annual pastures that are established each year. Within established permanent pastures there is usually only the need for maintenance fertilizer application to compensate any nutrient loss and maintain production.

Manures constitute a type of organic fertilizer, (they contain nutrients and organic matter), and it has been reported that the application of manures increases soil organic matter content more than the application of inorganic fertilizers (Karlen and Cambardella, 1996). As a result continual additions of manure usually increase the size of the microbial biomass (McGill *et al.*, 1986; Schnurer *et al.*, 1985; Haynes and Naidu, 1997), stimulates enzyme activity (Dick *et al.*,. 1988; Haynes and Naidu, 1997), and have beneficial effects on soil physical properties (Low, 1954; Haynes and Naidu, 1997), (see sections 2.3.1 and 2.3.2).

The extent of soil organic C increase per tonne of organic matter added is dependent on the degree of decomposition of the manures prior to application (Haynes and Naidu, 1997). Under arable systems the soil organic C content begins to decline as soon as manure applications cease (Johnston, 1975; Haynes and Naidu, 1997), this is due to the conditions in arable systems favouring decomposition (see section 2.4.2). Additions of organic fertilizers have been found to greatly increase earthworm populations (Mackay and Kladivko, 1985; Fraser, 1994), due to the increased food source; these increased numbers favour enhanced aggregation and macroporosity. Organic fertilizers provide a source of both nutrients and organic C, and these benefits merit further study, under dairy farming using annual pastures. The application of slurries through irrigation systems can be seen as a potential way to improve soil quality.

Long term fertilizer application is generally beneficial to soil quality because it results in higher soil organic matter returns and a greater biological activity than where no fertilizer is applied. A higher yield induced by fertilizer application generally means a higher return of organic matter to the soil in the form of decaying roots, litter and crop residues (Fraser, 1994). This can cause increases in the water stable aggregation, porosity, infiltration capacity and hydraulic conductivity and decrease bulk density (Haynes and Naidu, 1997). Nitrogen is the most commonly applied fertilizer and results from many long term studies show a general tendency of increases in soil C and soil microbial activity with substantive additions of N, compared to zero or low N additions (Paustian *et al.*, 1997). It can be surmised that since C and N are the major constituents of soil organic matter and their proportionality (i.e. C : N ratio) is relatively constant across a range of agricultural soils, then an adequate supply of N is required to build soil organic matter (Paustian *et al.*, 1997). The type of N fertilizer is also important, for example, if an ammonium based N fertilizer is applied in the absence of liming it can promote acidification (Thurston *et al.*, 1976; Paustian *et al.*, 1997), and a decrease in biomass C levels (Grace *et al.*, 1994). Long term experiments under both arable and pasture have demonstrated the beneficial effects of fertilizer (particularly N) applications in increasing C inputs to the soil and thus greatly increasing earthworm numbers (Fraser, 1994).

In many low fertility soils of Australia soil organic matter levels have increased above the virgin conditions due to the application of fertilizers (Russell and Williams, 1982; Grace *et al.*, 1994). Increased inputs of P and S accounted for annual increases of approximately 50 kg N ha^{-1} and 500 - 600 kg C ha^{-1} in long-term legume-based pastures in South Australia (Grace *et al.*, 1994). For arable crops N is usually most limiting, but within legume-based pastures it is usually P and S that limit production (Fraser, 1994). It follows that the application of superphosphate is especially beneficial for pasture production (Fraser *et al.*, 1993; Fraser, 1994), and thus soil organic matter accumulation.

It has been suggested that long-term lime application increases yield, organic matter returns, organic C content, biological activity and promotes favourable conditions for the improvement of various soil physical processes and properties, such as aggregation and infiltration(Haynes and Naidu, 1997). This is particularly evident in acidic soils, where liming facilitates the reduction of aluminium and manganese toxicity and alleviates any calcium deficiency (Haynes and Naidu, 1997). These improved soil conditions increase root growth and thus organic matter inputs by root turnover and root exudation of organic substances (Tisdall and Oades, 1979). This favours microbial biomass activity. Large quantities of organic material are supplied to soils from roots (Haynes and Naidu, 1997), especially under pastures and the maintenance of a suitable soil pH, with the use of lime can therefore improve organic matter returns. Liming can also increase the size and activity of some of the soil faunal components, such as earthworms, which are particularly sensitive to acidic conditions (Lee, 1985; Fraser, 1994).

Figure 2.6 essentially provides a summary of the effects of fertilizer, lime and manure addition on soil aggregation and improvement of soil structure, which are mechanisms for the improvement of soil quality.

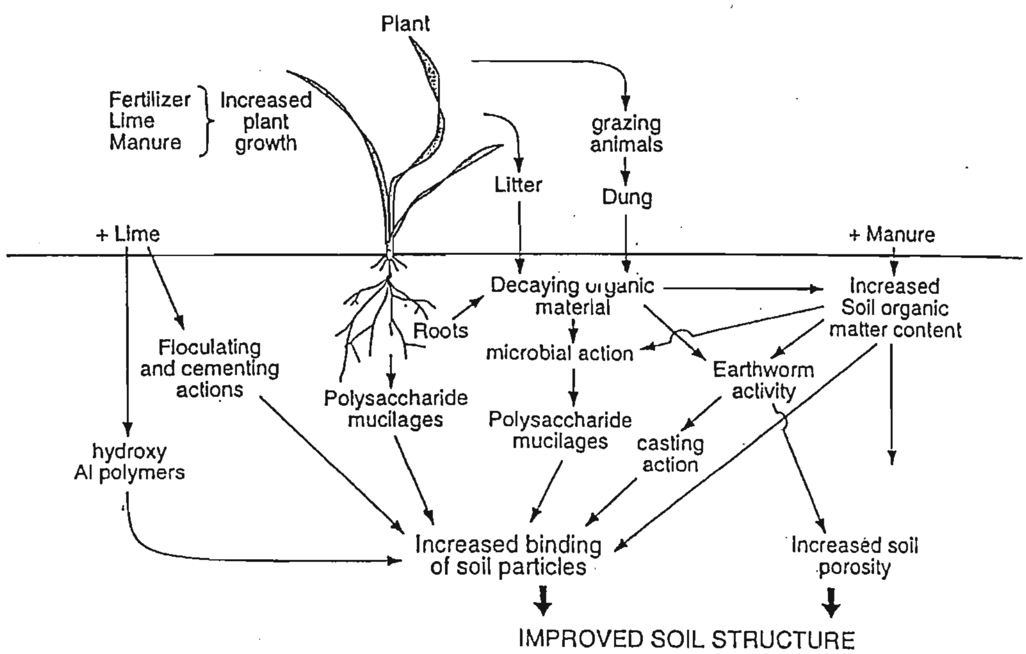


Figure 2.6 A conceptual model of the major effects that fertilizer, lime and manure have on improving soil aggregation and soil structural condition (Haynes and Naidu, 1997).

In order to maintain or improve soil quality with respect to fertilizer and lime application it is important that a balance in achieved between inputs and losses and that excessive fertilizer and lime application does not occur, as this could be both economically and environmentally unfavourable.

2.5.2 The effects of cattle treading

Animal treading in grassland ecosystems is known to affect the condition of both the soil and the vegetation (Sheath and Carlson, 1998), and can lead to soil compaction problems. Soil compaction represents the compression of the soil in response to applied pressure (Naeth *et al.*, 1990). The typical pressure exerted by cattle hooves is between 200 and 400 kPa (Haynes, 1995), so they represent a potential compacting force. During compaction the porosity is reduced and air expelled therefore reducing the macroporosity (Singleton and Addison, 1999), the pore continuity is however more affected than the total pore volume and this can reduce aeration and water and nutrient transmission within the soil.

Compaction occurs when the soil is so soft that the hooves of grazing animals cannot be supported by the surface and they press into the soil (Haynes, 1995). If a soil is compacted it's structure changes and this leads to conditions which are unfavourable for root growth, development and function of roots, such as, reduced soil aeration and porosity, reduced infiltration, increased bulk density, increased runoff and erosion and increased soil strength (Haynes, 1995). Treading damage effects pasture production either directly through damage to plants or indirectly through the associated soil conditions (Haynes, 1995). The incidence of treading damage is related to the original soil bulk density, soil moisture content, organic matter content, soil type and the grazing duration and intensity (Mulholland and Fullen, 1991). Under high stocking rates, intense grazing has been known to compact soils to a depth of 10cm (Lodge, 1954; Naeth *et al.*, 1990).

Soil water content is the most important factor affecting the severity of compaction or treading damage (Haynes,1995). Well drained soils tend to be less susceptible because they remain wetter for shorter periods of time. Compaction is maximum near field capacity (Orr, 1960; Naeth *et al.*, 1990). As soil moisture content increases it can reach the plastic limit, the point where hooves deform and compact the soil (Singleton and Addison, 1999). The organic matter content of the soil is another important factor effecting the degree of treading damage, because the lower the organic matter content, the lower the aggregate stability and the greater the susceptibility of the soil to compaction (Haynes, 1995). Organic matter serves to increase the soil's elasticity or resilience (i.e. its ability rebound back to its original state after a disturbance), (Seybold *et al.*, 1999), and this reduces treading damage.

Treading of grazing animals can have two main effects on soil physical properties; firstly when soils are close to saturation the hooves penetrate into the soil and produce a "puddling effect". This involves the remoulding of surface soil with the loss of large soil pores, as well as the tearing and burying of pasture plants. The soil aggregates are also disturbed and broken down. At lower soil moisture contents , around field capacity, puddling is less of a problem, but the soil is still plastic and malleable and can be compacted by treading (Haynes, 1995). The effects of treading tend to be "self perpetuating"; that is if a soil is partially pugged early in a season, then water will tend to remain on the surface for longer and the soil will be softer and wetter and therefore more susceptible to subsequent treading damage (Haynes, 1995).

Other effects from treading damage also need to be considered such as increased surface ponding, increased loss of nitrate due to anaerobic conditions (i.e. through denitrification), decreased root growth and the decrease in earthworm numbers (Gradwell, 1967; Cluzeau *et al.*, 1992; Singleton and Addison, 1999). All of these factors effect the overall pasture production and are therefore vitally important. Provided it remains under pasture, soil compacted by animal treading recovers its structure much faster than cropped soil compacted by cultivation machinery (Haynes, 1995). This is because of the extensive dense fibrous root system of grasses that extends through the surface layers of the soil and the characteristically large earthworm community that inhabits pasture soils. Both factors tend to promote macroporosity over time (Haynes, 1997).

In order to prevent treading damage, more attention should be payed to the critical factor of the soil's plastic limit and measures such as changing grazing intensity and timing and the use of lighter cattle should be implemented. By maintaining high levels of soil organic matter, litter and vegetative cover, a cushioning effect can be provided thereby minimising the negative effects of treading (Naeth *et al.*, 1990). The installation of drainage systems, although expensive may be an option for pastures that are particularly susceptible to treading damage (Haynes, 1995).

2.5.3 The effects of the grazing animal on nutrient cycling

Large quantities of nutrients are cycled within the ecosystem through the actions of grazing animals. Approximately 60 - 90 % of the ingested nutrients are returned to the pasture in the form of dung and urine (Barrow, 1987; Haynes and Williams, 1993). This does however vary between farming systems (Haynes and Williams, 1993). Largest losses are generally observed from dairy farms due to removals in milk (Hutton *et al.*, 1965, 1967, Haynes and Williams, 1993). Some of the nutrients are excreted mainly in the urine (e.g. K), while others (e.g. P, Ca, Mg, Cu, Zn, Fe and Mn) are returned mainly in the faeces. Some (e.g. N, Na, Cl and S) are excreted in both the urine and the faeces (Haynes and Williams, 1993). Although excretal patches may only cover 30 - 40 % of the pasture surface annually, the high nutrient input stimulates herbage growth so that it may represent 70 % of the total annual pasture production (Haynes and Williams, 1993). The extent of the nutrient returns and retention for dairy cows are shown in Table 2.5.

Table 2.5 Percentage excretion and retention of nutrient intake in lactating dairy cows (Data from Hutton *et al.*, 1965, 1967; adapted from Haynes and Williams, 1993).

	Retention (%)	Milk (%)	Urine (%)	Dung (%)
Nitrogen	5	15	55	25
Phosphorous	10	20	-	70
Potassium	2	8	75	15
Calcium	12	10	3	75
Magnesium	5	4	10	81
Sodium	5	8	55	32

From Table 2.5 it is evident that only a small proportion of the nutrients that are taken in are retained by the cows, and the majority are recycled in the form of dung and urine within the pastoral system. It is however important to realise that other losses do occur due to volatilisation, denitrification, leaching from urine patches and losses from dung and urine deposits in non pastoral areas such as races and the milking shed (Haynes and Williams, 1993). For these reasons the application of maintenance fertilizers is required.

Nutrient partitioning between dung and urine varies depending on diet (Barrow, 1987; Haynes and Williams, 1993); individual animals and between days (Hutton *et al.*, 1965, 1967; Betteridge *et al.*, 1986; Haynes and Williams, 1993). The pattern of excretal returns is also important because the more even the pattern, the more efficiently the nutrients are likely to be recycled within the pasture system (Haynes and Williams, 1993). For example under extensive set-stocking systems there is ample opportunity for animals to camp in favoured areas (e.g. on the top of hills, under trees, along fence lines, around water troughs). Since the animals generally spend a greater proportion of their time in the camp areas than elsewhere, dung and urine is preferentially deposited in these areas. This results in a net transfer of nutrients from the main grazing areas to the camp sites (Betteridge *et al.*, 1986; Haynes and Williams, 1993). By contrast under an intensive rotational grazing system the high stocking rates reduce the tendency for camping and nutrients are cycled more efficiently (Haynes and Williams, 1993).

The release of N in faeces is determined by the rate of microbial mineralisation, because the bulk of the N is in organic form and must therefore first undergo mineralisation before it is released in mineral form (Floate, 1970; Haynes and Williams, 1993). The availability of P from dung is initially the consequence of leaching of water-soluble inorganic P (Floate, 1970; Haynes and Williams, 1993). The major mechanism controlling movement of P from faeces is the rate of physical breakdown. The release of K and Na from faeces is rapid because the bulk of these elements are in water-soluble form and it was reported by Weeda, (1977) that the level of exchangeable K below dung pats peaked one month after application. The release of Ca and Mg was slower and levels in the soil only peaked after four months (Weeda, 1977).

There is normally a marked positive pasture growth response in a urine patch and this is commonly attributed to added N and usually lasts for two to three months (Ledgard and Saunders, 1982; Ledgard *et al.*, 1982; Haynes and Williams, 1993). The typical application rates of N, S and K per urine patch are 1000 kg N ha^{-1}, 35 kg S ha^{-1} and 900 kg K ha^{-1} (Haynes and Williams, 1993). The release of these nutrients from urine patches is therefore very important for nutrient cycling within a grazed pastoral system. The application rate of urine is typically about 10 litres m^{-2} (Hogg, 1981; Haynes and Williams, 1993), and this can result in ponding at the soil surface and the initiation of preferential flow (Williams *et al.*, 1990; Haynes and Williams, 1993), which results in substantial losses due to leaching. Over a seven month period following a urine event it was noted the vast majority of N and K absorbed by the pasture plants occurred within 12 cm of surface and that at least in the short term, nutrients that moved below 15 cm from the surface represented a loss (Williams *et al.*, 1989; Haynes and Williams, 1993). Extensive spatial variability exist in the extent of macropore flow within pastures (Williams *et al.*, 1990; Haynes and Williams, 1993), and this will have a large effect on the fate of nutrients added in the form of urine. Urea hydrolysis occurs rapidly after urination and large amount of NH_4^+ accumulate in the soil (Haynes and Williams, 1993). Significant gaseous losses due to NH_3 volatilisation occur from urine patches following urination, but the conversion of NH_4^+ to NH_3 is the major process regulating the potential loss of NH_3 from soils (Haynes and Williams, 1993).

From the above discussion it is evident that grazing animals play a major role in nutrient cycling within pastoral systems and the extent of returns is surprisingly large. If correctly managed (i.e. by maximising returns) it can have a significant effect on the overall pasture production and in some parts of the world fertilizer recommendations for pastures are made based on nutrient cycling models (Haynes and Williams, 1993).

2.5.4 The effects of pasture type

The type of pasture is also likely to influence soil quality, although there has been little research on this topic. Two major factors are likely to be important, these are (i) the amount of above and particularly below-ground biomass produced and (ii) the length of time the pasture is present (see section 2.4.1). The below-ground biomass production is indicated by the root length and root mass densities. Pastures in comparison with arable agriculture generally have a positive effect on the physical and biological properties of the soil. They effect soil quality because of the associated effects of organic matter production, root structure, vegetative cover and aggregate stability. It has been shown that plants that result in the most improvements in soil structure produce the most microbial biomass (Lynch and Bragg, 1985; Carter, 1986; Perfect *et al.*, 1990). Soil microbial biomass would be expected to increase with root growth rate and rooting density (Carter, 1986; Drury *et al.*, 1991).

Italian ryegrass (*Lolium multiflorum*), has a shallow and fairly small root system (Anonymous, 1986), it is also an annual pasture that has to be resown every year. Although it has other benefits such as high feed quality it is fairly unfavourable in terms of soil quality, when compared to other pasture species because of its small root system and annual nature. It's root length density and root mass density are shown in table 2.6.

From the table it can be seen that Italian ryegrass has low root length and mass densities compared to perennial ryegrass (*Lolium perenne*) and annual ryegrass. This has important consequences in terms of soil quality because it is an indication of the below-ground biomass production. Prairie grass (*Bromus unilodies*) can be considered to be the most unfavourable in terms of soil quality because of it's low root length and mass densities. It is generally accepted that root length density correlates with aggregate stability (Kay, 1990; Drury *et al.*, 1991).

It was shown by Clement and Williams (1958), that perennial ryegrass had a greater positive effect on aggregate stability than white clover (*Trifolium repens*). It was also shown that perennial ryegrass increased aggregate stability but red clover (*Trifolium pratense*), had no significant effect (Stone and Buttery, 1989). The difference was attributed to perennial ryegrass having a greater root mass, and root length density and therefore favouring improved aggregate stability. Although white and red clover are legumes and provide a source of nitrogen, the improvement of soil physical properties still have a beneficial effect on soil quality.

Perennial ryegrass has a higher root length and root mass density than annual ryegrass, and therefore as expected it was shown by Haynes and Francis, (1993), to have a higher mean weight diameter (mm) and hot water-extractable carbohydrate(mg C kg $^{-1}$), both of which are favourable in terms of soil quality. Perennial ryegrass is also favoured over annual ryegrass due to it's perennial nature. Although perennial ryegrass requires fairly intensive management, for example in the form of irrigation (Anonymous, 1986), good production can be achieved, if favourable conditions prevail.

Kikuyu (*Penisetum clandestinum*) is considered to be one of the best pastures for the improvement of soil quality (Anonymous, 1986). This is because of the high organic matter production, extensive root system (see section 2.5.4), and its tolerance to various adverse conditions. Kikuyu also has a high tolerance to bad management practices and does not require intensive management. Kikuyu increases the soil organic matter content which is favourable for soil structure, other soil properties, soil faunal activity, especially, earthworms which help improve soil structure and overall the presence of a kikuyu pasture is therefore favourable for soil quality. Kikuyu is able to out produce most pastures at 500 mm of rainfall as well as provide the highest yield per litre of applied water (Anonymous, 1986), and is therefore productive at both ends of the scale. Kikuyu is an extremely useful pasture and has a place in most pastoral systems.

Table 2.6 Table showing the root length and root mass densities of several grass species (Adapted from Haynes and Francis, 1993).

Species	Root length density ($cm\ cm^{-3}$)	Root mass density ($kg\ m^{-3}$)
Perennial ryegrass	6.9	4.4
Annual ryegrass	5.4	3.7
Italian ryegrass	2.2	2.0
Prairie ryegrass	0.91	0.86
Perennial white clover	2.2	1.8

2.6 DISCUSSION AND CONCLUSIONS

It is important to realise that a pastoral system is very complex and a thorough understanding of various key processes within the system is essential. The use of a holistic approach to the understanding and management of agricultural systems has consistently been conveyed in the literature (Gregorich *et al.*,1994), and is essential because of the complex interrelations that occur within these systems. This approach is particularly useful when soil quality indicators are being used to compare the effects of management practices on soil condition (Karlen and Cambardella, 1996). The complexity of pastoral systems and the fact that soil quality is site and function specific and therefore dependent on climatic, soil, topographic, economic and social conditions (Karlen *et al.*, 1997), means that soil chemical, physical and biological properties need to be considered in relation to the system being used and the study locality. Land owners and managers should strive to prevent degradation of the soil resource, especially beyond a critical level where the soil's ability to recover or restore itself is either lost or severely disrupted and soil quality becomes a limiting factor to pastoral production. The capacity of a soil to resist and recover from minor stresses and disturbances can be enhanced by management (Seybold *et al.*, 1999). For example, increasing soil organic matter content and soil biological activity will enhance it's ability to recover from disturbances such as compaction and cultivation.

In order to achieve an improvement in the quality of the soil resource there is the need for a realistic (i.e. affordable, easy, practical and easily reproduceable), soil measurement procedure that facilitates the monitoring of the effects of management practices on soil quality. This monitoring program must be available to land owners and managers and not be limited to people with scientific backgrounds. The generation of a basic implementation program will also benefit the drive towards the sustainable use of the soil resource. The correct choice of quality indicators will, however be essential.

Agricultural practices and soil organic matter dynamics are intimately linked and virtually all facets of management impact the amount of C which can be maintained in the soil (Paustian *et al.*, 1997). For example, it increases greatly under pastoral management and decreases rapidly under arable cropping. It is vital that the most suitable management practices are chosen so that soil organic matter content is maintained at an acceptable level. Management of soil organic matter content is central to the management of soil quality since organic matter plays central roles in the soil chemical (through supply of mineral N, P and S and by its effect on cation exchange capacity and buffering capacity), physical (through its aggregating effect) and biological (through acting as an energy source for soil biota) properties of soils. In addition, soil organic matter also increases the ability of the soil to recover from minor stresses and disturbances (i.e. its resilience) imposed by factors such as compactive forces and cultivation.

It follows, then, that in practical terms the more organic matter added to the soil the better, and the more infrequent soil disturbances (e.g. cultivation) occurs (which promotes soil organic matter breakdown) the better. The presence of any crop is better than no crop and a high-yielding crop is better than a poor one. This is because a high-yielding crop will have greater root and above ground growth and therefore it will return more organic material to the soil. Similarly fertilization is beneficial due to the associated increase in organic matter production and return. It is important that land owners manage soil organic matter content, soil quality and soil resilience so that sustainable management is practised. Prevention of soil degradation is a more profitable practice than trying to ameliorate it.

The maintenance of soil structure is an essential component of sustainable land management and the loss or deterioration of soil structure through unfavourable management practices can limit plant production. In order to ensure sustained pasture productivity, it is important that physical properties do not deteriorate to a level where production, management and off site environmental difficulties (e.g. runoff and erosion) are encountered (Singleton and Addison, 1999). Aggregation is vitally important for the maintenance of soil structure and can be used both as an indicator of soil structural stability and soil quality (Haynes and Beare, 1996). The realisation that declines in soil structural properties can not continually be overcome or compensated for by increased inputs, (such as fertilizer additions) is important, and it is therefore essential that soil structural condition is maintained.

The effects of long term agricultural practices on soil quality are usually mediated principally through their effects on the soil organic matter content (Haynes, 1997). Typically there is an increase under pasture and a decrease under arable cropping (Haynes and Beare, 1996). This results in permanent pastoral systems having different effects on the soil chemical, physical and biological properties, compared to annual or arable systems. The positive effects of pasture has given rise to the development of ley-arable rotation systems which facilitate the maintenance of soil quality. The reason for the increase under pasture is mainly due to below-ground rhizodeposition of organic C (Haynes and Francis, 1993). The root mass and length densities are important factors influencing the effect that a crop has on soil quality and the larger the root mass the greater the rhizodeposition of organic material and thus the larger the microbial biomass that is supported (Haynes and Francis, 1993). The type of pasture grasses present can also be important since they can effect the amount of organic matter deposition through differences in root growth and turnover. These positive effects under pasture are negated by time spent under arable cropping (Haynes and Francis, 1993). Grasses are particularly favourable to soil aggregation because of their extensive rooting systems and the associated improvement in soil structure by the binding of macroaggregates with fine roots and vesicular-arbuscular mycorrhiza, fungal hyphae and the binding of microaggregates with humic materials and mucilages formed during decomposition of roots and hyphae (Oades, 1984, Stone and Buttery, 1989).

The grazing animal plays a vital role in nutrient cycling within pastoral systems (Haynes and Williams, 1993), and the returns from dung and urine are surprisingly high and contribute considerably to the maintenance of soil fertility and thus to the overall sustainability of the system. These returns have economic consequences and need to be considered when fertilizer recommendations are being made. The cycling of nutrients and organic matter by grazing animals also promotes soil biological activity. In addition, the trampling effects of grazing livestock on wet soils can induce soil compaction. Thus stock management can influence soil quality and it needs to be considered when working with pastoral soils.

Effects of annually cultivated pastures, which are used extensively in the South African dairy industry, on soil quality is, as yet, unstudied. However, their effect is suspected to be similar to the that of arable agriculture in that annual cultivation will promote the loss of soil organic matter content. Such a loss may well contribute greatly to the pastoral production problems that are presently facing the Dairy industry. The concepts of soil quality and soil resilience and the use of chemical, physical and biological indicators of soil quality to investigate the comparative effects of presently-used annual and permanent pastoral systems will be an important step in developing a sustainable pastoral production system in the dairy industry.

CHAPTER 3

COMPARATIVE EFFECT OF ANNUAL AND PERENNIAL PASTURES ON SOIL ORGANIC MATTER CONTENT, RELATED MICROBIAL PROPERTIES AND AGGREGATE STABILITY

3.1 Introduction

The central concept of soil quality, as the "capacity of the soil to function" (Doran and Parkin, 1994; Doran *et al.*, 1996) can be used as an appropriate assessment tool because it serves as an umbrella concept for examining and integrating relationships and functions among various biological, chemical and physical parameters that can be measured and which are important for sustainable agricultural and environmental systems (Karlen *et al.*, 1997).

Concern has arisen in recent years over the possible soil degradation that is occurring under annually cultivated ryegrass dairy pastures in the Tsitsikamma. The circumstantial evidence for a loss of soil quality includes poor germination and early growth of grass seedlings, lack of pasture longevity, evidence of surface and subsurface compaction, significant losses of soil through wind erosion and suggestions that there has been a substantial loss of soil organic matter. By contrast, such observations have not been made regarding soils under permanent kikuyu grass pastures which also occur throughout the region.

Soil organic matter plays a central role in determining the chemical, biological and physical properties of soils. A loss of soil organic matter therefore often leads to a loss of soil quality (Gregorich *et al.*, 1994; Karlen and Cambardella, 1996). For example, a decrease in the soil biological activity is of particular concern (Doran and Parkin, 1994; Gregorich *et al.*, 1994) since biologically mediated processes are essential to the ecological functioning of soils. Soil structural decline is also a potential problem since there is a close relationship between soil organic matter content and water stable aggregation in soils (Chaney and Swift, 1984; Haynes and Naidu, 1997).

There is increasing evidence that measures of the size and activity of the soil microbial community (e.g. microbial biomass C, basal respiratory activity and soil enzyme activity) hold considerable potential as early indicators of soil degradation or improvement (Sparling, 1992). In particular, such parameters are sensitive to changes in total soil organic matter content that are detected (Powlson and Jenkinson, 1981; Carter, 1986; Sparling, 1992). For that reason, such measures are now commonly used when investigating the effects of various agricultural management practices on soil quality (Seybold *et al.*, 1998).

Observations in the Tsitsikamma region have revealed that soils can be divided into three broad groups. In the east sandy soils predominate whilst in the higher rainfall western area the soils are much more developed and podzolic in nature. In the central region, sandy loam soils dominate. Constraints to pasture growth may differ on these different soils and the nature and consequence of soil degradation could also differ.

The first part of the study involves the investigation of the effect of past management practices (i.e. annual cultivation, permanent pasture or undisturbed veld) and texture (i.e. sand, silt and clay content) on soil organic matter status, the size and activity of the soil microbial population (thus nutrient supplying ability), enzyme activity and aggregate stability. This will provide base-line information on the overall condition of the soils in the region and suggests whether remedial practices need to be implemented. Such base-line information is required before suggestions for changes in present pasture management practices can be made. The inclusion of undisturbed sites from each area allowed the effects of agricultural activity on the soil condition to be gauged.

3.2 Materials and Methods

Four commercial dairy farms were selected from within the Tsitsikamma region of the Eastern Cape, South Africa. These were named "Brandkop" ($34^0$00' 517"S and 24^0 16' 838"E), classified texturally as a loamy sand (Soil Classification Working Group, 1991) in the eastern part of the region, "Lanark" (34^0 02' 787"S and 24^0 26' 497"E) and "Heidehof" (34^0 04' 243"S and 24^0 15' 491"E), classified as sandy loams (Soil Classification Working Group, 1991) in the centre of the region and "Kenmore" (34^0 01' 046"S and $23^0$56' 161"E), classified as a loam (Soil Classification Working Group, 1991) in the western region of the district.

The geology of the Tsitsikamma shows an origin of predominantly Table Mountain Sandstone (Eastern Cape Farming Manual, 1984). The soils at the sites were classified as Groenkop form, (Gk), (orthic A, over podzol B, over saprolite), Bosrug family (Soil Classification, Working Group, 1991) at Brandkop, Cartref form (Cf), (orthic A, over E horizon, over lithocutanic B), Frosterley family (Soil Classification Working Group, 1991) at Lanark and Heidehof a Kroonstad form, (Kd), (orthic A, over E horizon, over G horizon), Morgendal family at Kenmore (Soil Classification Working Group, 1991). The clay contents of the soils ranged from about 8 -15 % in the eastern region, 16 - 24 % in the central region and 26 - 35 % in the western region of the district.

The Tsitsikamma generally experiences mild winter and summer temperatures with a range in mean monthly air temperature from10.0^{0}C in August to 24.7^{0}C in February (Eastern Cape Farming Manual, 1984). The Tsitsikamma is generally a high rainfall area and the mean annual rainfall is approximately 710 mm in the eastern region, 951 mm in the central region and 1125 mm in the western region (Eastern Cape Farming Manual, 1984). The rainfall distribution is comparatively even throughout the year, but does, however, tend to peak in Autumn and Spring, while December, January and February are somewhat drier months.

Four experimental fields were chosen on each farm. At Brandkop, Lanark and Kenmore the land uses were two annually cultivated ryegrass pastures, a permanent kikuyu pasture and an undisturbed veld or native vegetation. At Heidehof, there was only one annual pasture and two permanent kikuyu pastures. The reason for this was that at Heidehof there was a field that had been annually cultivated for approximately 20 years but an area at the side of that field had been left unfertilized under kikuyu grass [kikuyu grass (Fo)] for the same period of time.

At each farm annual pastures were sown with perennial ryegrass (*Lolium perenne*),and had been annually cultivated for longer than 10 years. Similarly the permanent kikuyu grass (*Pennisetum clandestinum*) pastures had remained uncultivated for greater than 10 years. Except for the kikuyu grass (Fo) field at Heidehof, each field had a history of annual applications of fertilizer (N, P, K and Mg) and lime at commercially recommended rates. At Brandkop, the annual pastures were not irrigated but the kikuyu pasture was. At Lanark and Kenmore annual pastures were irrigated but the kikuyu ones were not. At Heidehof, the annual and kikuyu grass (Fo) were not irrigated but the other kikuyu pasture was. All of the pastures were rotationally grazed with dairy cows although the kikuyu grass site (Fo) site had a history of only occasional grazing.

Areas under undisturbed native vegetation were identified on unused parts of each farm and ranged from false macchia in the east to Knysna forest in the west (Acocks, 1988). At Brandkop the natural vegetation was sparse consisting of small bushes and a few grasses, at Lanark the vegetation was more prolific and dense. At Heidehof the vegetation was a more productive mixture of small bushes, shrubs and grasses, while at Kenmore it consisted of a short coastal forest with a distinct litter layer at the soil surface. Some of the dominant species at each of the sites were classified; at Brandkop (*Stoebe plumosus*, *Leucadendron salignum* and *Rhodocoma gigantea*), at Lanark (*Rhodocoma gigantea, Podalyria glanca* and *Metalasia muticata*), at Heidehof (*Rhus lucida, Rhus glanca* and *Tarchonanthus camphoratus*) and at Kenmore (*Olinia ventosa*, *Crysanthemoides monilefera* and *Helichrysum petiolare*).

Study fields were approximately 20 ha in size. At Heidehof, the annually cultivated field (cultivated for about 20 years) had a strip of about 10 m wide at one side which was the kikuyu grass (Fo) site. Three replicate plots (100 m^2) were randomly chosen within each study field and 25 soil samples to a depth of 10 cm were randomly sampled from each plot using a tube sampler (25 mm inner diameter). Samples from each plot were bulked. For areas under undisturbed vegetation, an area of approximately 20 ha was marked out and it was sampled in the same way. The bulked field-moist samples were mixed and split into three sub-samples. One sub-sample was sieved (<2mm) and stored at 2 ^{0}C for less than four weeks prior to microbiological and biological analyses. Another sub-sample was air-dried, sieved (<2 mm), ground (<0.5 mm) and stored for subsequent chemical analysis. The third sub-sample, for analysis of aggregate stability, was sieved and the 2 - 6 mm diameter aggregates collected and air dried.

Soil pH was measured with a glass electrode using a 1:2.5, soil : water ratio. The soil organic C content was determined colorimetrically by the Walkley and Black dichromate oxidation method (Blakemore *et al.*, 1972). Microbial biomass C was estimated by the method of Vance *et al.* (1987), based on the difference between C extracted with 0.5 M K_2SO_4 from chloroformfumigated and unfumigated soil samples using a K_c factor of 0.38. The microbial quotient was calculated by expressing microbial biomass C as a percentage of total soil organic C. Basal respiration was determined by placing 30g of oven dry equivalent of field moist soil in 50 ml containers and incubating the sample in the dark at room temperature (25 ^{0}C) in an air-tight standard 1L jar along with 10 ml of 1M NaOH. The CO_2-C evolved was determined after 2,5 and 10 days by titration (Anderson, 1982). The microbial metabolic quotient was calculated as basal respiration (ug CO_2-C h^{-1}) expressed per mg of microbial biomass C. Arginine ammonification rate was measured by the method described by Franzluebbers *et al.* (1995) using an incubation time of three hours and a temperature of 25 ^{0}C. The rate of fluorescein diacetate (FDA) hydrolysis was estimated following the method of Schnürer and Rosswall (1982) using an incubation period of two hours and temperature of 30 ^{0}C with the concentration of hydrolysed fluorescein being determined colorimetrically at 490 nm.

Aggregate stability was measured using a wet sieving technique (Haynes, 1993). The equivalent of 30g air-dried 2 - 6 mm soil aggregates were transferred to the uppermost of a set of three sieves having 2.0, 1.0 and 0.5 mm diameter apertures. The water level was maintained at a level to ensure that the aggregates on the upper sieve were just submerged at the highest point of oscillation. The oscillation rate was 25 cycles per minute, the amplitude of the sieving action was 35 mm and the period of sieving was 15min. The results were expressed as a mean weight diameter (mm), which is the sum of the fraction of soil remaining on each sieve after sieving for the standard time multiplied by the mean diameter of the intersieve aperture. The maximum value for mean weight diameter is 4 and the minimum is 0.25 mm.

3.3 Results

The $pH_{(water)}$ values for the experimental sites are presented in Figure3.1 and ranged from 4.1 under native vegetation at Kenmore to 6.9 under annual ryegrass at Kenmore. The acidic soil at Kenmore is podzolic in nature with an E horizon at 25 - 30 cm. However, at all the sites, fields under dairy pasture had a history of lime applications. As a result, there was no discernable trend in pH values with land use.

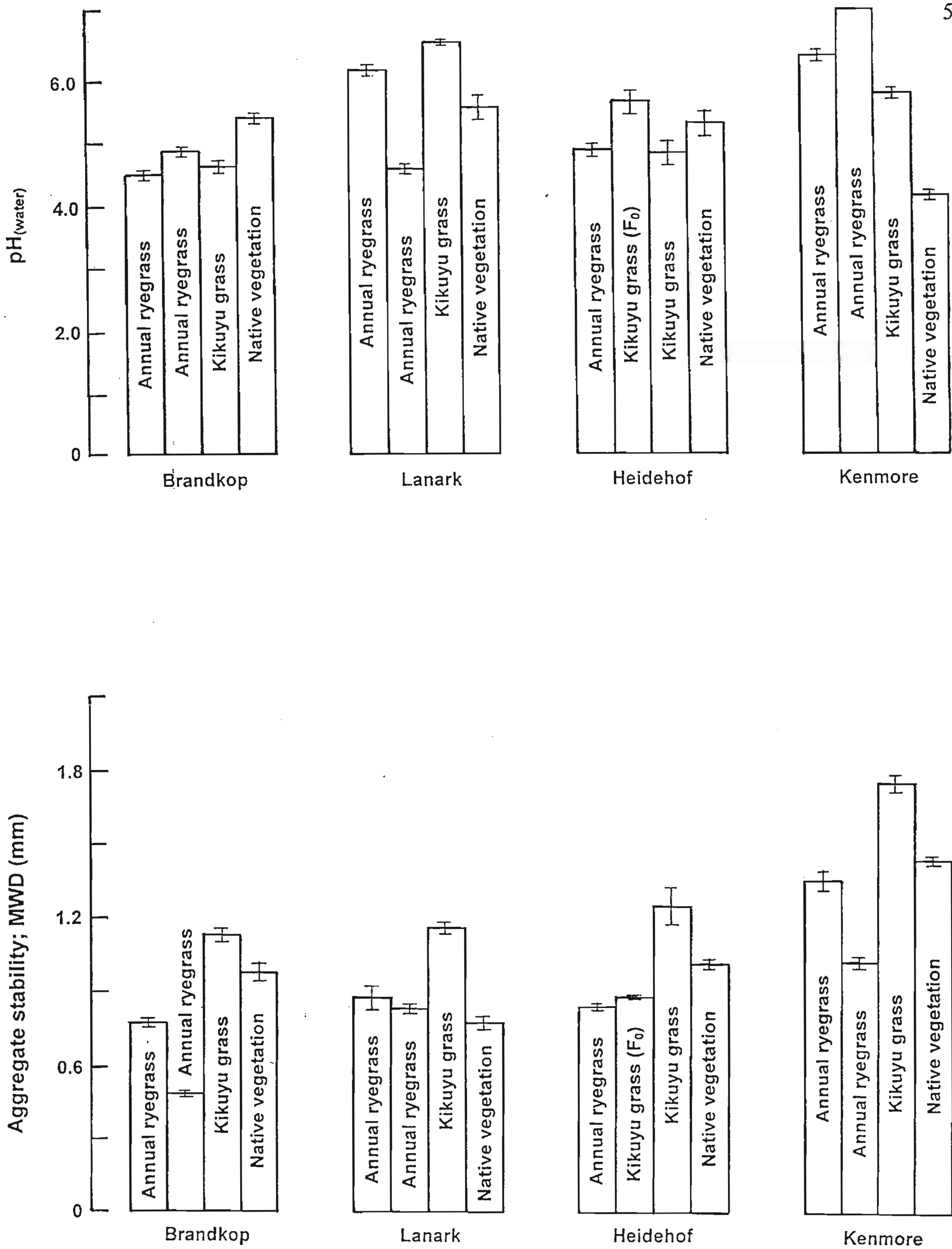


Figure 3.1 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on soil pH and aggregate stability, measured as mean weight diameter (MWD). Bars indicate ± standard error (S.E.) of the means.

Recorded values for aggregate stability were all relatively low compared with a maximum obtainable value of 4 mm (Figure 3.1), thus emphasising the structurally unstable nature of these sandy soils. Under native vegetation, aggregate stability was higher at Kenmore than other sites. Values were higher under kikuyu grass than other land uses at each of the sites. At Brandkop, Heidehof and Kenmore, values under annual ryegrass tended to be lower than those under native vegetation.

The organic C contents under native vegetation increased in the order Brandkop < Lanark < Heidehof < Kenmore (Figure 3.2). At Brandkop, Lanark and to a lesser extent Heidehof, organic C content was greater under kikuyu grass than under native vegetation; the effect was most marked at Brandkop. At Kenmore, however the reverse was the case and organic C content was greatest under native vegetation. Brandkop was the only one of the four sites where the organic C content was higher under annual pasture (27 and 36 g kg^{-1}) than under native vegetation (18 g kg^{-1}). At Kenmore the organic C levels were relatively high (> 53 g kg^{-1}) even under the annual pasture.

The K_2SO_4 - extractable C concentrations ranged from 32 mg kg^{-1} under annual pasture at Lanark to 372 mg kg^{-1} under permanent kikuyu pasture at Kenmore (Figure 3.2). In comparison with values for organic C, those for K_2SO_4-extractable C under native vegetation were unexpectedly low at the Lanark site. Indeed values followed the order Lanark < Brandkop < Heidehof < Kenmore. The permanent kikuyu pastures had the highest values at all four sites. Surprisingly, at least one of the annual pastures per site tended to have a similar or higher extractable C content than under native vegetation.

Microbial biomass C concentrations ranged from 94 mg kg^{-1} under annual pasture at Brandkop to the very high value of 3359 mg kg^{-1} under permanent kikuyu pasture at Kenmore (Figure 3.3). Under native vegetation microbial biomass C followed the trend Brandkop < Lanark = Heidehof < Kenmore. Microbial biomass C was the highest under permanent kikuyu pastures at all four sites and the lowest under annual pastures at all sites except one of the annual pastures at Lanark. In comparison with values for organic C and K_2SO_4-extractable C, values for microbial biomass C were very low under annual pastures at Brandkop and unexpectedly high under annual pastures at Lanark (Figures 3.2 and 3.3). At Heidehof, microbial biomass C was much lower in the first (1230 mg kg^{-1}) than the second kikuyu pasture (2349 mg kg^{-1}).

Values for the microbial quotient (Figure 3.3) ranged from 0.28 % under annual pasture at Brandkop to 5.28 % under annual pasture at Lanark. Trends for microbial quotient with land use did not necessarily follow those for microbial biomass C. For example, at Heidehof and Kenmore values were highest for kikuyu grass pastures, but this was not the case at Brandkop and Lanark. Nonetheless, like microbial biomass C concentrations, values under annual ryegrass were particularly low at Brandkop and surprisingly high at Lanark.

Basal respiration rates ranged from 5 ug CO_2-C g^{-1} day^{-1} under annual pasture at Brandkop to 76 ug CO_2-C g^{-1} day^{-1} under permanent kikuyu pastures at Kenmore (Figure 3.4). Basal respiration under native vegetation followed the order Brandkop ≤ Lanark < Heidehof < Kenmore. It was markedly higher under kikuyu grass than the other land uses. The metabolic quotient was exceptionally high under annual ryegrass at Brandkop (Figure 3.4). At each site, lowest values were recorded under native vegetation although values were also very low under one of the annual ryegrass fields at Lanark.

Trends with land use for both FDA hydrolytic activity and arginine ammonification rate (Figure 3.5) were broadly similar. At Brandkop, Lanark and Heidehof, kikuyu pastures showed the highest values. At Kenmore, kikuyu grass showed higher values than annual ryegrass but as with organic C content, highest values were recorded under native vegetation.

Linear correlation coefficients between the various properties measured in this study are shown in Table 3.1. The soil organic C, microbial biomass C, K_2SO_4-extractable C, basal respiration and aggregate stability were significantly correlated with each other. FDA hydrolysis rate was also closely correlated with the above parameters, but arginine ammonification rate was not significantly correlated with either K_2SO_4-extractable C or basal respiration. The microbial quotient was significantly correlated with microbial biomass C but not with organic C. Indeed, microbial and metabolic quotients were generally poorly correlated with the other measured properties but were negatively correlated with each other. Aggregate stability was more closely correlated with K_2SO_4-extractable C, microbial biomass C and basal respiration than with organic C content.

The measured properties were used to generate a correlation matrix and their significance determined using simple linear regression. The statistical program Genstat 5, version 4.1 was utilized.

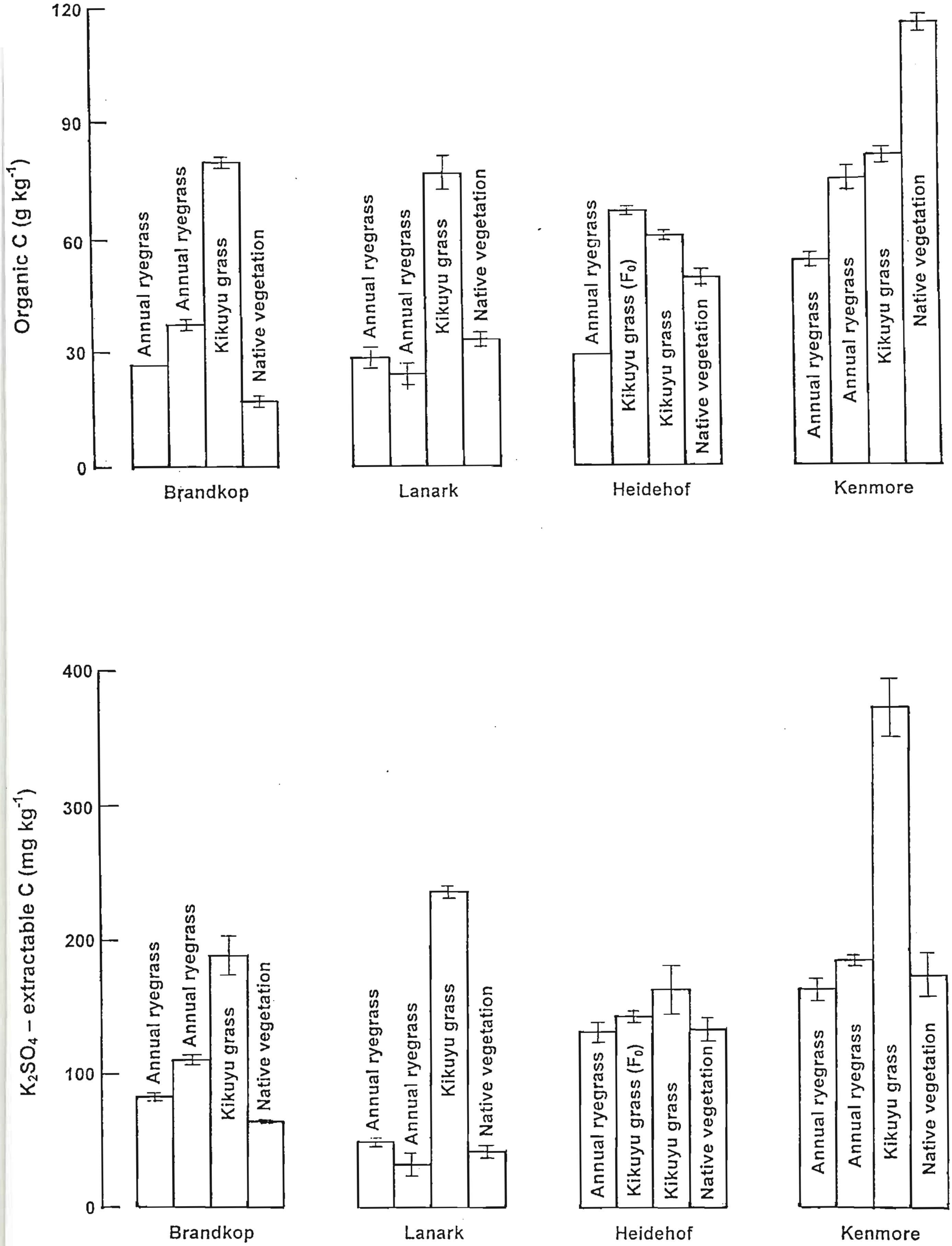


Figure 3.2 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on soil organic C and K_2SO_4 - extractable C. Bars indicate ± standard error (S.E.) of the means.

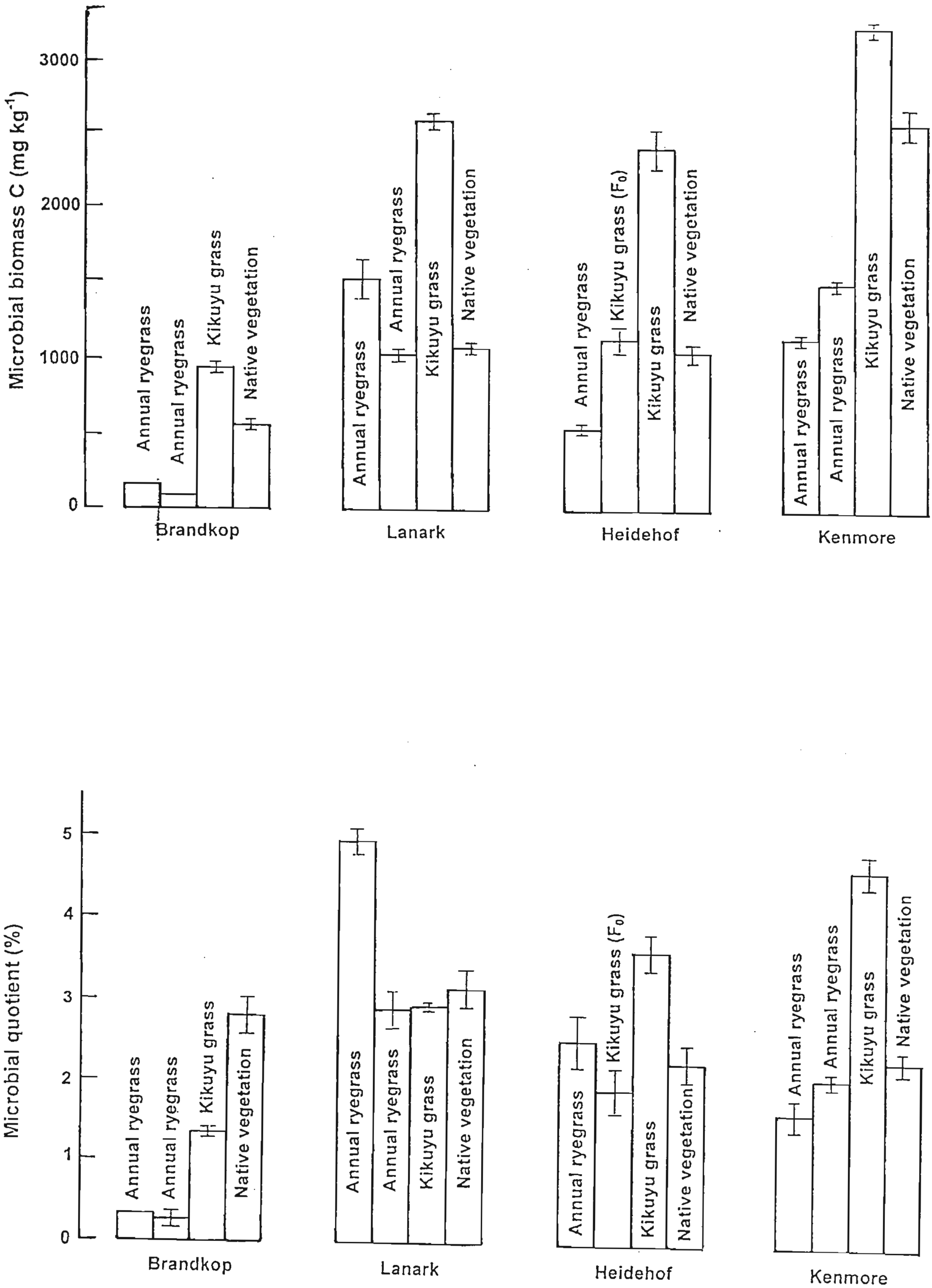


Figure 3.3 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on microbial biomass C and microbial quotient. Bars indicate ± standard error (S.E.) of the means.

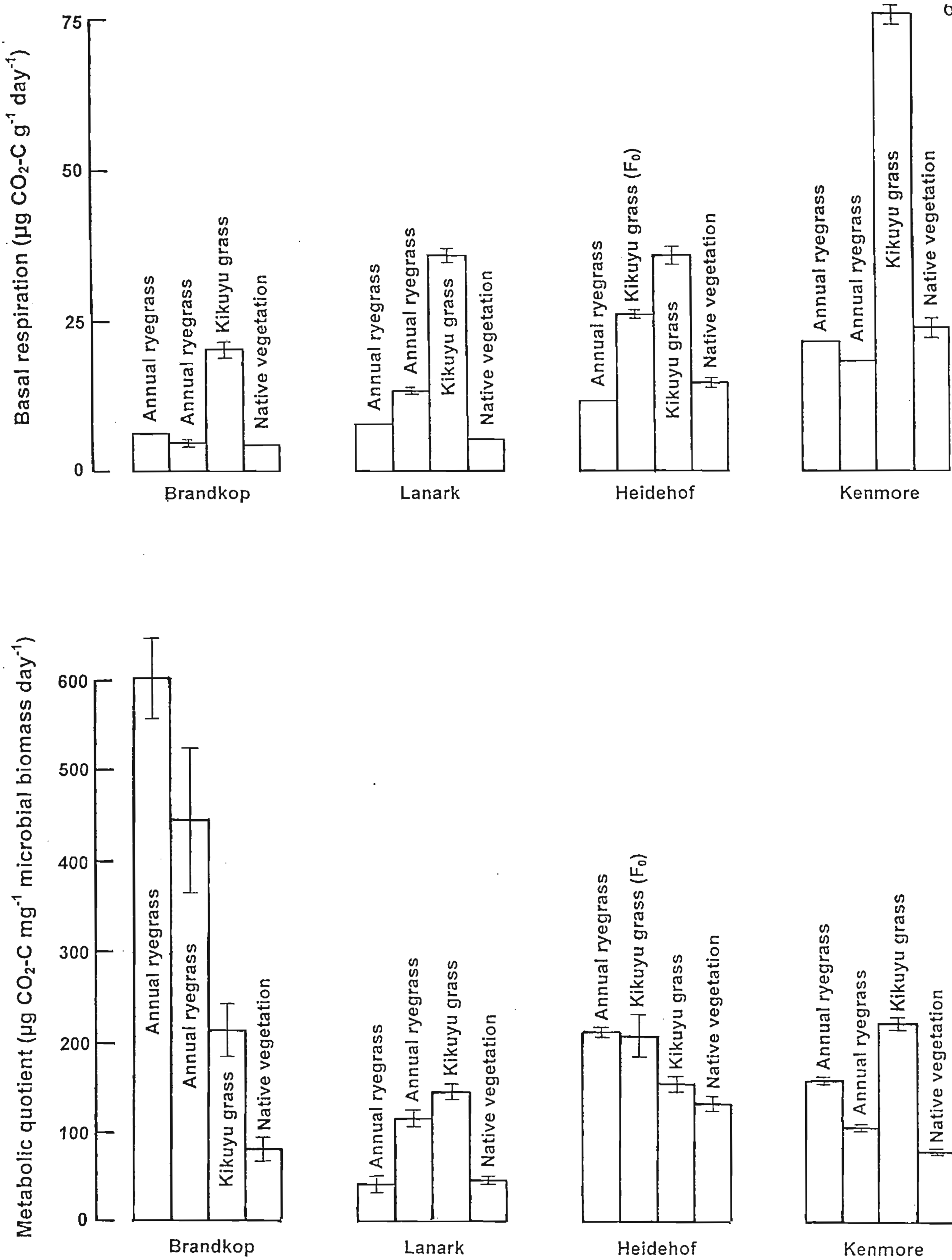


Figure 3.4 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on basal respiration and metabolic quotient. Bars indicate ± standard error (S.E.) of the means.

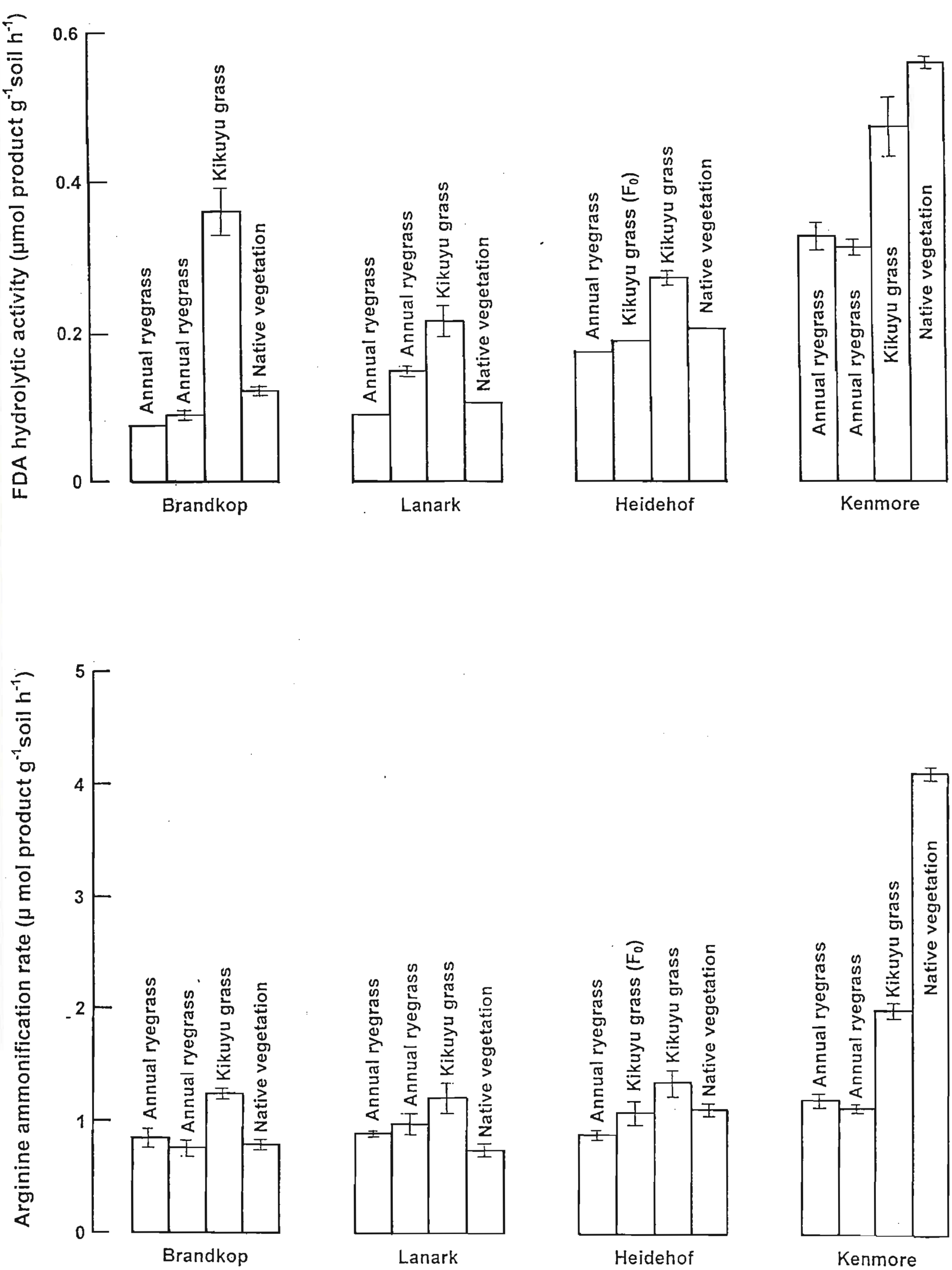


Figure 3.5 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on FDA hydrolysis activity and arginine ammonification rate. Bars indicate ± standard error (S.E.) of the means.

3.4 DISCUSSION

3.4.1 Soil pH

The pH values found under the native vegetation (Figure 3.1) are an indication of the original soil pH that predominated before agricultural activity began. The most noticeable pH effect is that the values under the native vegetation are similar at Brandkop, Lanark and Heidehof, but they are about one pH unit lower at Kenmore. This lower pH is largely climate driven and attributable to higher rainfall at Kenmore which has resulted in the development of a soil form, with a characteristic E horizon (Soil Classification Working Group, 1991). In the case of this E horizon it has developed due to the presence of the less permeable underlying G horizon. It does, however, still have a podzolic nature i.e., vertical eluviation of organic matter, iron and aluminium and bases out of the A and E horizons occurs. This characteristic leaching results in the "stripping" of bases and the associated acidification of the soil profile (He *et al.*, 1999).

The high level of organic matter found under the native forest vegetation at Kenmore (with a distinct litter layer at surface), (Figure 3.2) is probably also partly responsible for the lower pH. This accumulation increases the soil's cation exchange capacity and results in an associated increase in the H^+ ion saturation of the exchange complex (Vitosh *et al.*, 1997) and therefore leads to a decrease in soil pH. The decomposition of organic material produces organic acids which also have an acidifying effect (Blevins and Frye, 1993), and therefore add to the acidification of the soil profile.

The fact that the soil is naturally acidic at Kenmore has necessitated the application of large regular applications of lime in order to promote optimum pasture production. Indeed, applications of about 2 Mg ha^{-1} are generally applied to fields on a biennial basis. For this reason, soil pH under the annual pastures and the permanent kikuyu pastures is considerably greater than that under native vegetation. This is evident from the fact that Kenmore has both the lowest and the highest pH values of all the sites, under the native vegetation and annual pasture respectively.

Pasture management at Brandkop has, however, had an overall acidifying effect, with all the values under pasture being lower than those under the native vegetation. This is presumably attributable to the acidifying effect of nitrogenous fertilizer application plus the low buffering capacity of the soil. In general, annual applications of fertilizer N to annual ryegrass and kikuyu pastures in the region amount to about 200 and 250 kg N ha^{-1} respectively. The nitrification of NH_4^+ originating from the applied fertilizer results in the release of H^+ ions into the soil system (Blevins and Frye, 1993), which facilitate the acidification of the soil. The sandy nature of the soil at Brandkop and the lower organic C content means $N0_3^-$ is more susceptible to leaching. If this $N0_3^-$ is leached (commonly with Ca^{2+} and Mg^{2+} as counter ions) the H^+ is left in the soil system and acidification is permanent (He *et al.*, 1999). In addition the sandy soil will have a low buffering capacity so that changes in pH will occur relatively rapidly. In general, soil pH values under dairy pastures will reflect a balance between acidification processes such as fertilizer N applications and N mineralisation under annual pastures and the ameliorative effect of regular lime applications.

Table 3.1 Linear correlation coefficients (r)[a] between various measures of organic matter, size and activity of the microbial biomass and aggregate stability

Soil property	Arginine ammonification	FDA hydrolysis	Aggregate stability	Basal respiration	K_2SO_4 extractable C	Microbial biomass C	Metabolic quotient	Microbial quotient
Organic C	0.81***	0.87***	0.68**	0.58*	0.70**	0.72**	-0.19^{ns}	0.01^{ns}
Microbial quotient	0.08^{ns}	0.14^{ns}	0.44^{ns}	0.45^{ns}	0.19^{ns}	0.64**	-0.66**	
Metabolic quotient	-0.21^{ns}	-0.25^{ns}	-0.33^{ns}	-0.07^{ns}	0.03^{ns}	-0.45^{ns}		
Microbial biomass C	0.65**	0.71**	0.83***	0.82***	0.70**			
K_2SO_4 extractable C	0.44^{ns}	0.74***	0.79***	0.90***				
Basal respiration	0.40^{ns}	0.65**	0.81***					
Aggregate stability	0.65**	0.86***						
FDA hydrolysis	0.85***							

[a] Statistical significance shown: ^{ns}Not significant, * P≤0.05, ** P≤0.01, *** P≤0.001

3.4.2 Soil organic carbon content

The fact that organic C content of soils was positively correlated with most of the other measured properties (Table 3.1) demonstrates the central role that organic matter plays in determining soil quality. Changes due to soil management practices do, however, occur very slowly and are often difficult to measure accurately against a large background soil organic matter content already present (Paustian *et al.*, 1997). For that reason, in this study, fields with a known long-term history under either annual or permanent pasture were chosen.

The increase in organic matter content from east to west (Brandkop < Lanark < Heidehof < Kenmore) (Figure 3.2) under native vegetation reflects increases in rainfall, plant biomass production and soil clay content. For example, at Brandkop, the vegetation was sparse grassland with a few low bushes and a clay content of about 8 -15 %, while at Kenmore the vegetation was short coastal forest and the clay content was about 26 -35 %. Thus, at Kenmore, there is a greater dry matter production (and therefore greater return of organic material to the soil) and the higher clay content, which can have a considerable effect on the higher equilibrium organic matter levels (Sollins *et al.*, 1996), which provides a greater protective effect for organic matter. Indeed, there is commonly a positive correlation between soil organic C and clay content (Spain, 1990), since absorption of organic molecules onto clay mineral surfaces provides a mechanism of stabilisation of organic C against microbial attack (Baldock and Nelson, 2000). This protective effect is demonstrated by the fact that even the annual pastures at Kenmore had higher organic matter contents than those at other sites.

Where native vegetation is replaced by improved pasture there can also be an appreciable increase in organic matter content (Haynes and Williams, 1993) and this accounts for the increase under permanent kikuyu pasture at Brandkop, Lanark and Heidehof (Figure 3.2). This increase in organic matter is attributable to the very large inputs of organic matter (particularly via root turnover) (Haynes and Beare, 1996), that occur under permanent grazed pastures. Organic matter inputs also occur above-ground by return of litter and animal dung to the soil surface (Haynes and Williams, 1993). Often fertilization and irrigation play an important role since they promote increased plant dry matter production (and therefore larger organic matter returns) (Karlen and Cambardella, 1996). The opposite effect has occurred at Kenmore where the implementation of a permanent pasture has resulted in a decrease in organic C. This presumably reflects the loss or dilution of the surface organic layer and horizon which was present on the forest floor, during conversion of the soil to agricultural use. It should, however, be realised that the rate of organic matter accumulation and the time taken to reach equilibrium varies considerably, depending on factors such as soil type, climate and management (Haynes and Beare, 1996) and will therefore differ from site to site.

Surprisingly the organic C content is higher under the annual pastures than the native vegetation at Brandkop. This is probably because of the extremely low organic matter production under the native vegetation and a considerably higher dry matter production under the annually cultivated pasture, due to inputs such as fertilizer and the nutrient cycling via the grazing animal. As expected, at all the other sites the organic matter content under the annual pastures was lower than that under either the native vegetation or permanent kikuyu pastures. This reflects the degrading effect that annual cultivation has on the soil organic matter content.

Conventional cultivation causes disturbance to the soil and the aggregates are broken apart and the organic matter that was previously physically protected by aggregate structure is exposed and mineralised by soil microbes (Haynes and Beare, 1996). The mixing of the soil during cultivation introduces more oxygen into the soil and this increases the activity of the aerobic microorganisms (Cannell and Hawes, 1994). The result of the increased surface area of organic matter for microbial attack and the increased aeration is that there is a flush of microbial activity and degradation of organic matter. As a consequence, annually cultivated soils generally have a much lower organic matter content than those that are not subject to cultivation (Haynes and Beare, 1996).

As in several other studies (Kassim *et al.*, 1982), the K_2SO_4 - extractable C fraction was used as a measure of a labile pool of soil organic C. It represented only 0.25 to 0.60 % of the total organic C content of soils and is probably mainly soluble C in soil solution (Haynes, 2000). The fact that it is a labile, soluble C fraction means that changes and / or differences in C turnover may be detectable even where total organic C content remains unchanged or shows a different trend. Thus, whilst K_2SO_4-extractable C was positively correlated with soil organic C content (Table

3.1), it did show some trends with treatment that differed from those for organic C. For example, extractable C concentrations were highest under permanent kikuyu pastures at all the sites, even at Heidehof and Kenmore where this was not the case for the organic C (Figure 3.2). This reflects the large turnover of organic matter that occurs under a highly productive, grazed pasture (Barrow, 1987; Haynes and Williams, 1993), which maintains high concentrations of labile organic matter in soil solution (Haynes, 2000). Because soluble C is directly available as a substrate for microbes, it is not surprising that the size (microbial biomass C) and activity (basal respiration) of the microbial community showed a similar trend being greatest under kikuyu pastures at each of the sites. The positive effect of fertilizer applications and intensive grazing on soil microbial activity is also shown by the larger size and activity of the microbial biomass under kikuyu pasture than the kikuyu grass (Fo) site at Heidehof (Figures 3.3 and 3.4), even though both sites had a similar organic C content.

3.4.3 Size and activity of the microbial biomass

The microbial biomass represents the living component of the soil organic matter (Sparling, 1985; Wardle, 1992) and is the primary agent of the soil ecosystem responsible for litter decomposition, nutrient cycling and energy flow (Wardle, 1992). It has a high turnover rate and responds rapidly to changes in C availability (Haynes, 1997). It also responds very rapidly to anthropogenic disturbance and stress and is therefore a very useful ecological indicator (Wardle, 1992). Microbial biomass C is generally positively correlated with soil organic matter content since the higher the organic matter content the more substrate is available for microbial growth (Sparling, 1997; Dalal, 1998). Indeed in this study organic C and microbial biomass C were positively correlated (Table 3.1).

As expected microbial biomass C follows a similar trend to organic C and increases under the native vegetation from Brandkop through to Kenmore and is highest under kikuyu pasture at each of the four sites. At Kenmore, the lower microbial biomass C and basal respiration under native vegetation than kikuyu pasture may not only be related to greater concentrations or turnover of labile organic C under kikuyu grass. For example, soil pH (Figure 3.1) may also have had an effect, as the microbial biomass is often related to pH, and low biomass values are often recorded from soils with low pH (Jenkinson *et al.*, 1979; Vance *et al.*, 1987a; Wardle, 1992), as soil acidity is known to be an important factor that can limit the size and activity of the microbial community (Tate, 1995). Thus, the low pH under native vegetation at Kenmore (i.e. 4.1) may have inhibited microbial activity.

The microbial quotient is the proportion of the total organic C that is living and is expressed as; microbial biomass C / total organic C, (often 1- 5 %). It can be a more useful measure than either measure considered individually as it is a ratio and avoids the problems of working with absolute values and allows for comparisons across soils with different organic matter contents. Shifts in the microbial quotient act as early warning for ecosystem-level effects of environmentally harmful practices (Insam and Domsch, 1988; Wardle, 1992). It can also be used as a sensitive indicator of changes in organic matter availability (Carter, 1986; Sparling, 1992). The fact that the microbial quotient was significantly correlated with microbial biomass C values but not with those for organic C emphasises the fact that changes in the size of the microbial biomass can occur independently of changes in organic C content.

Although it has been noted by a number of workers that the microbial quotient typically increases with increasing clay content up to 50% (Dalal, 1998), in this study under native vegetation values were higher at Brandkop and Lanark than at Heidehof and Kenmore (Figure 3.3). The lower values at Kenmore than Brandkop are surprising since soil at the former site had a higher clay and organic matter content. Nevertheless, Sparling (1992) and Haynes (1999b) also recorded decreases in the microbial quotient with increasing clay content. The stabilising effect of clay probably means soils with a high clay content contain a larger proportion of inert, stabilized organic matter, thus there is a decrease in the microbial quotient.

Basal respiration is a well established parameter to monitor the organic matter decomposition (i.e., the C mineralisation or CO_2 evolution) and can give an indication of the organic matter quality (i.e., the readily mineralizable C). It is also used as an index of the microbial activity (Haynes, 1999b). The most obvious trend in the basal respiration results (Figure 3.4) is that the highest values occur under the permanent kikuyu pastures at all four sites. This reflects trends in K_2SO_4 - extractable C and microbial biomass C and, indeed, basal respiration was more closely correlated with these indices than with soil organic C content (Table 3.1). Thus the greater the amount of soluble C, the greater the size of the microbial biomass and the greater the respiratory loss of CO_2 from the soil.

The metabolic quotient or respiratory quotient provides a useful measure of the microbial efficiency and is expressed as, basal respiration / microbial biomass C. The measurement is based on the ecological theory that in young and developing soils there is less competition for energy and less incentive for efficient use of substrate C (therefore a higher metabolic quotient) whilst in mature climax ecosystems such as grasslands and forests, where equilibrium conditions are attained or approached, the microflora become more efficient at conserving C (Insam and Domsch, 1988; Insam and Haselwanter, 1989), and the metabolic quotient is lower. Results of this study lend support to the above theory since values for the metabolic quotient were notably low under undisturbed native vegetation at all four sites (Figure 3.4).

An increase in the metabolic quotient had been interpreted as a response by microflora to adverse conditions (either environmental stress or disturbance) (Wardle and Ghani, 1995). That is, when the microbial community is under stress a greater proportion of substrate C is respired as CO_2 rather than converted to cellular C. The negative correlation between metabolic quotient (Table 3.1) and microbial quotient has been observed many times (Sparling, 1997). It occurs because factors that limit the size of the microbial biomass are generally those that cause stress to it and the metabolic quotient is consequently raised.

The two highest values for metabolic quotient were recorded under annual pasture at Brandkop. These two fields had unusually low values for microbial biomass C and the microbial quotient and these were not explicable in terms of low organic C or K_2SO_4-extractable C levels. Thus, factors other than a poor supply of substrate C seemed to be limiting the size of the microbial biomass at these two sites. The soils at Brandkop are very sandy and have a low water retention capacity. Whilst the kikuyu pasture was under irrigation the two annual ryegrass fields were not The very dry season in the study year (only 583 mm compared to mean of 944 mm), (Rainfall data from Brandkop 1989 - 2001), meant that at Brandkop, at the time of sampling, most of the ryegrass was wilting and dying due to water stress. Water stress was probably also limiting microbial activity. Interestingly, the annual ryegrass pasture and kikuyu grass (Fo) at nearby Heidehof were also under dryland and also had unexpectedly high values for metabolic quotient (Figure 3.4).

It is important to note that caution needs to be exercised when interpreting changing values for the metabolic quotient since they do not necessarily always reflect microbial stress. For example, a change in the fungal : bacterial ratio can be important since bacterial communities are less efficient at converting substrate C into cellular C than fungi (Kazunori and Oba, 1994). In addition, recent incorporation of substrate C (e.g. plant residues) could preferentially stimulate microbial respiration and cause a high metabolic quotient (Sparling, 1997). In the present study it is unknown whether a change in management affected the fungal to bacterial ratio but certainly, crop residues had not recently been incorporated at any of the sites.

The rate of FDA hydrolysis is considered as an index of the overall microbial activity because its hydrolysis is carried out by active cells using a variety of enzymes including lipases , proteases and esterases (Schnürer and Rosswall, 1982; Alef and Kleiner, 1987; Bonde *et al.*, 2001). Generally more than 90% of the energy flow in a soil system passes through microbial decomposers, therefore an assay which measures microbial decomposer activity will provide a good estimate of the total microbial activity (Adam and Duncan, 2000). For this reason FDA hydrolysis has been widely accepted as an accurate and simple method for measuring the total microbial activity. Similarly, arginine ammonification rate can also be used as an index of soil microbial activity since most heterotrophic soil microorganisms possess endocellular ammonifying capacity and its rate has been shown to be closely related to microbial activity (CO_2 evolution) in laboratory studies (Alef and Kleiner, 1987).

The rates of FDA hydrolysis and arginine ammonification were closely correlated with each other. Both were strongly correlated with soil organic C content, as shown by Deng and Tabatabai, (1997), but surprisingly they were less strongly correlated with microbial biomass C (Table 3.1). While the FDA hydrolysis rate was correlated with basal respiration, arginine ammonification was not. A major contributor to the closeness, or otherwise, of these correlations was that at the Kenmore site, organic C content, and the rates of arginine ammonification and FDA hydrolysis were considerably higher under native forest vegetation than kikuyu pasture yet the reverse was the case for microbial biomass C, microbial quotient and basal respiration. That is the smaller microbial biomass under native forest had a lower respiration but greater enzymatic capacity to ammonify arginine endocellularly or hydrolyse FDA. It seems possible that the microbial community in the acidic (pH $_{(water)}$ = 4.1) forest soil at Kenmore differed appreciably from that which predominated in the others (particularly that under the kikuyu pasture at Kenmore). For example, a low pH would favour fungi over bacteria and vice versa (Wood, 1995).

At the other three sites, kikuyu pastures showed the highest rates of arginine ammonification and FDA hydrolysis which is in agreement with measurements of microbial biomass C and basal respiration. This again emphasises the pasture effect that a highly productive, grazed permanent pasture has on soil microbial activity.

3.4.4 Aggregate stability

Since soil organic matter is central to the formation and stabilization of soil aggregates (Tisdall and Oades, 1982) and there is normally a close correlation between soil organic matter content and water stable aggregation in soils (Chaney and Swift, 1984; Haynes and Naidu, 1997). The significant correlation between organic C and aggregate stability observed suggests that over the range of soils and sites studied, the binding actions of humic substances were playing an important role in soil aggregation (Haynes and Beare, 1996). Nonetheless, the significantly closer correlations with K_2SO_4-extractable C, microbial biomass C and basal respiration indicate that the size and activity of the soil microbial biomass can have an extremely important role in aggregation.

The reason for the closer correlation between aggregate stability and the above microbial measurements than with organic C lies in the fact that the highest aggregate stability values occurred under the permanent kikuyu pasture at all four sites, but this was not the case for organic C. This can be attributed to the "rhizosphere effect" of the permanent pastoral systems, since grasses characteristically have a large below-ground biomass with a fine, highly ramified root system (Haynes and Beare, 1996). Aggregation is promoted by the production of large quantities of polysaccharide binding agents by the large microbial biomass in the pasture rhizosphere and the enmeshing effects of the fine grass roots and associated mycorrhizal hyphae (Tisdall and Oades, 1979). The production of polysaccharides is of particular importance since they play an essential role in the polysaccharide-mediated stability of macroaggregates (Roberson *et al.*, 1991).

Both the amount of organic matter and the clay content have a direct effect on the aggregate stability and the highest values were, as expected found at Kenmore which had the highest organic matter and clay contents. As already noted, adsorption of organic molecules onto clay particles essentially provides the main mechanism for aggregation (Baldock and Nelson, 2000). The low clay content at Brandkop means that it has a lower potential to store organic matter and it is believed that in sandy soils such as these, the enmeshment of organo-mineral and sand particles by the fine roots and associated mycorrhizal fungal hyphae may be the principal mechanism of macroaggregation (Degens *et al.*, 1996).

The negative effect of cultivation on aggregate stability is mediated mainly through the loss of organic matter and associated soil microbial activity (Karlen *et al.*, 1994). In agreement with values for organic C and the size and activity of the microbial biomass, aggregate stability was lower under annual than kikuyu pasture at each site (except at Lanark), (Figure 3.1). Such a finding confirms field observations that have revealed surface capping, poor germination and early seed growth, lack of pasture longevity, evidence of surface and subsoil compaction and loss of soil via wind erosion under annual pastures. Such problems are generally not encountered under kikuyu pastures.

3.5 Conclusions

In comparison with undisturbed, native vegetation, soils under both annually cultivated and permanent pasture have gained soil organic matter on the very sandy, low rainfall eastern end of the Tsitsikamma. By contrast, at the higher rainfall western end where the native vegetation consists of coastal forest, there has been a loss of soil organic matter under both types of pasture. Despite this, soil organic C content was lower under annual ryegrass than permanent kikuyu pasture at all the sites reflecting the degrading effect of annual cultivation on soil organic matter.

The positive effect of a permanent grazed pasture on soil microbial activity was demonstrated by grazed kikuyu pastures showing highest values for extractable C, microbial biomass C and basal respiration at all the study sites, because the greater the amount of soluble C, the greater the size of the microbial biomass and the greater the respiratory loss of CO_2 from the soil.

The benefit of using factors such as microbial biomass C and microbial quotient as early indicators of possible changes in soil organic C was illustrated by the fact that the microbial quotient was significantly correlated with microbial biomass C values but not with organic C. Thus emphasising the fact that changes in the size of the microbial biomass can occur independently of changes in organic C content and therefore serve as an early indicator.

It was suggested that soil moisture stress under annual dryland pastures limited soil microbial activity and resulted in very high values for the metabolic quotient being recorded in the eastern end of the region. At the western end, the acidic soil under native forest vegetation had a low basal respiration and metabolic quotient, but high values for FDA hydrolysis and arginine ammonification. It is suggested that the composition of the microbial community in this soil may have differed from that in the other soils, all of which had substantially higher pH values and were not under forest.

The lower organic matter under annual ryegrass than permanent kikuyu pastures resulted in a concomitantly lower aggregate stability under annual pastures. This means that soils under annual pasture will be more susceptible to soil structural breakdown and compaction. This aspect is examined in the following chapter. The most obvious way to improve soil organic matter status and related microbiological and physical properties in the surface soil under annual pastures would be to change from conventional to zero tillage. In the near future it is suggested that the practice of direct drilling annual pastures should seriously be considered. In terms of future avenues of study, the structure or composition of the soil microbial community can be investigated to decide whether or not it has an effect on the chosen soil factors.

CHAPTER 4

PHYSICAL CHARACTERISTICS OF THE SOIL PROFILE UNDER ANNUAL AND PERENNIAL DAIRY PASTURES

4.1 Introduction

In previous studies in the Tsitsikamma region (see chapter 3), it was shown that long-term kikuyu pastures often result in an accumulation of organic matter compared to native vegetation, whilst annually cultivated pastures generally result in a substantial loss of organic matter. Corresponding changes in aggregate stability were also recorded. Hence, these changes are expected to result in marked changes in soil physical properties. Visual observations have also suggested that surface and/or subsoil compacted layers have developed under annual pastures, thus restricting root growth and overall herbage production.

The effects of conventional cultivation, i.e. tillage (annual pastures) on soil structure are not all favourable and the conversion from pasture to cultivated land typically yields substantial reductions in aggregate stability within a few years (Tisdall and Oades, 1982; Elliott, 1986; Angers *et al.*, 1992; Paustian *et al.*, 1997). This can, in turn, set in motion a wide range of degradative processes including the deterioration of soil structure and the acceleration of soil erosion (Lal, 1993). The reduction in organic matter and loss of macroaggregate stability, as observed under annual pastures, renders the soil more sensitive or susceptible to physical degradation such as structural breakdown and compaction caused by tillage and traffic such as farm machinery and grazing animals (Haynes, 1995). This can cause associated reductions in infiltration, aeration, porosity, pore continuity, pore size distribution, root penetration and density and water holding capacity (Blevins and Frye,1993), all of which are highly unfavourable and detrimental to overall pasture production. Various ameliorative processes, such as subsoiling or additional passes with a secondary tillage implement, may then be necessary in order to sustain pasture production and produce a suitable seedbed for resowing (Haynes, 1995).

In contrast, soil physical properties are generally positively effected by the implementation of a permanent pastoral system (Haynes, 1995), due, mainly to the increase in organic matter content and the associated increase in the size and stability of the soil aggregates (Cannell and Hawes, 1994). This in turn has favourable effects on the soil structure and other physical properties. It should, however, be noted that the grazing animal, through treading damage, can greatly modify soil physical properties under pasture (Haynes and Williams, 1993) and therefore alter expected trends.

If a basic soil physical property, such as soil water retention, is considered its importance is evident because it regulates the storage and movement of water within the soil profile and ultimately plant growth (Chen and Wheater, 1999). It is sensitive to both the inherent properties of the soil and past management practices since it is influenced by both the texture and the structure of the soil (Cresswell *et al.*, 1992).The infiltration of water into the soil is a dynamic process (Banton, 1993; Bosch and West, 1998) which is also effected by the soil physical condition. Initially the rate of infiltration is high because of a large water potential gradient near the surface, this slows to a nearly constant rate as the potential approaches unity (Radcliffe and Rasmussen, 2000) and this final steady state is referred to as saturated hydraulic conductivity (K_s). This is, however, considerably effected by factors such as crusting and/or compaction and hence land utilization is vitally important due to its direct effect on the soil physical properties.

Another physical property, adequate aeration, is important because of the need for aerobic respiration of plant roots and micro organisms (Glinski and Stepniewski, 1983) and the general functioning of the soil system. Gas exchange in soils is influenced by the size, distribution and the continuity of the pores (Beven and German, 1981; Ball *et al.*, 1988). Pore continuity can be more important than the size or number of pores per unit volume of soil (Glinski and Stepniewski, 1983), because of its relation with aeration and gaseous exchange. Soil pores and their continuity are also important in terms of root penetration, as the roots will favour the path of least resistance and tend to follow pores their own size or larger, rather than penetrate a soil ped (Roseberg and McCoy, 1992). Air flow (aeration) through the soil is also an indicator of the physical condition of the soil in terms of its structure and stability and it has the advantage of being essentially a non-destructive measurement (Smith *et al.*, 1998).

In this study, the effects of annual and permanent pastures on the soil physical attributes (water retention, bulk density, saturated hydraulic conductivity, porosity, penetrometer resistance and air permeability) and root density are compared with those under the native vegetation. In addition, the effects of subsoiling an annual pasture, where a subsoil compacted layer had been identified, on the soil physical properties and root density were also investigated.

4.2 Materials and Methods

The data collection was carried out on soils from the same four selected farms used in chapter three. These are at "Brandkop" (34^0 00' 517"S and 24^0 16' 838"E), classified texturally as a loamy sand (Soil Classification Working Group, 1991) in the eastern part of the region, "Lanark" (34^0 02' 787"S and 24^0 26' 497"E) and "Heidehof" (34^0 04' 243"S and 24^0 15' 491"E), classified as sandy loams in the centre of the region and "Kenmore" (34^0 01' 046"S and 23^0 56' 161"E), classified as a loam in the western region of the district.

At each farm annual pastures were sown with perennial ryegrass (*Lolium perenne*),and had been annually cultivated for longer than 10 years. Similarly the permanent kikuyu grass (*Pennisetum clandestinum*) pastures had remained uncultivated for greater than 10 years and all of the pastures were rotationally grazed with dairy cows . The native vegetation was the natural undisturbed vegetation on unused parts of the farm. The effect of land use (annual pasture, permanent kikuyu and native vegetation) was investigated at all of the chosen sites. Data was, however, only collected from one annual site at each of the farms due to constraints on core numbers.

To investigate the effect of subsoil tillage (subsoiling) on physical properties, adjoining annual ryegrass fields at Lanark were chosen that had been under the same grazing management for the previous 10 years. In both, a subsoil compacted layer at about 15 cm was identified by examination of the walls of six pits dug randomly in each field. One field was subsoiled to a depth of 40 cm using a tractor-mounted Brazilian Baldan ripper with a tine spacing of 50 cm. The soil water content at the time of subsoiling was about 20 % w/v and soil consistence was friable.

The unsubsoiled field was the annual ryegrass pasture described above and was sampled as outlined previously. The adjoining field was sampled seven months after subsoiling from the randomly chosen areas (see above) both "below" and "between" the tines. That is, in a 20 cm wide area down the tine slots (identified as slightly raised areas running in rows down the field surface) avoiding the central slot area and in a 20 cm wide area in the centre between adjacent tine slots.

Undisturbed soil cores were collected for the determination of water retention, porosity, bulk density, air permeability and saturated hydraulic conductivity using core rings (75 mm i.d. and 50 mm high). At each site the same replicate plots as described in chapter 3 were used. Duplicate cores were randomly taken from within each plot from the 0 - 15 and 15 - 30 cm layers and results meaned. The core rings were hammered vertically into the soil using a core sampler. The samples were taken when the soil was at field capacity to prevent disturbance and add homogeneity to sampling. In order to achieve this, fields were heavily irrigated and allowed to drain prior to sampling. The cores were securely wrapped in lids during transportation and carefully trimmed to the edge of the core cylinder with a sharp blade once in the laboratory. A pre-weighed cheesecloth was held onto the bottom of the core by means of an elastic-band to prevent any soil loss.

The cores were then massed, saturated by capillary action for 48 h at atmospheric pressure in a water bath containing distilled water, re-massed to obtain the saturated water content and then placed on a sand bath tension table (Smith and Thomasson, 1974). In the higher range of matric potential (typically between 0 and -10kPa) samples were equilibrated against a hanging water column. The mass of the core was recorded at matric potentials of -1, -2, -3, -4, -5, -6, -8, -10 kPa after equilibration at each tension for 48 h. In the lower matric potential range (-30,- 60 -100 and -1500 kPa) pneumatic pressure (pressure plates) was used to determine the water retention potential of the soils. The samples were placed on an initially saturated porous plate within the pressure chamber and by increasing the pressure within the chamber, progressively smaller sized pores were drained through the porous plate to the exterior. Sample equilibration was achieved once there was no longer any water loss from the sample this took approximately six to seven days. The cores were then oven dried at 105 ^{0}C and massed to enable the calculation of the mass water content at each matric potential.

Undisturbed soil cores were also used to determine the saturated hydraulic conductivity (K_s), using the constant head method (Klute and Dirksen,1986). The cores were saturated by capillary action in a distilled water bath and the volume of water transmitted per unit time recorded. The constant head maintained was 50 mm and this was achieved by the use of a mariotte bottle system. A steady state was assumed when the volume per unit time became constant. The K_s of an undisturbed soil core was calculated according to Darcy's law:

$$K_s = V.L / (A.t. \Delta H) \text{ ....Eq.1.1}$$

where K_s is the saturated hydraulic conductivity, V is the volume of water, L is the length of the sample core, A is the cross sectional area of the sample core, t is the time and ΔH is the hydraulic potential difference between inflow and outflow boundaries.

The soil bulk density was determined using the undisturbed soil cores. The soil moisture content was determined gravimetrically (mass water content) at each matric potential after oven drying the core samples at 105 °C for 48 h. The bulk density of the core was obtained by dividing the mass of oven dried soil by its volume (volume of core ring). This was then used to transform the mass water content to an equivalent volumetric water content using the relationship:

$$O_v = O_m \times P_b \times P_w^{-1} \text{....Eq1.2}$$

where , O_v is the volumetric water content (m^3 m^{-3}), O_m is the mass water content (kg kg^{-1}), P_b is the bulk density of the soil (kg m^{-3}) and P_w is the density of water (kg m^{-3}).

A simplified air permeameter, based on the design of Corey (1986), and modified by Moodley (2001) was used to measure air permeability. The intact soil cores were placed in a sleeve to form an air-tight seal and a constant air supply supplied via an air pressure regulator vertically upwards through the sample core. A flow meter comprising of a water manometer plus capillary outflow tube was used to measure the air pressure drop across the core (Moodley, 2001). The air permeability was measured at matric potentials of -10 kPa and -100 kPa to negate the influence of water content and allow comparisons to be made.

For each sample three inflow pressures were maintained and the flow rate obtained. The air permeability (K_a in m^2) was then calculated by the equation of Corey (1986).

$$\mathbf{K_a = n_a\ VL / (A\ P_m\ g\ h)}....\text{Eq. 1.3}$$

where n_a is the air viscosity (1.835 x 10^5 Pa at 20 ^{0}C); V is the measured air-flow rate ($m^3\ s^{-1}$); L is the sample height (m); A is the sample cross-sectional area (m^2); P_m is the manometer fluid density (for water this is 998 kg m^{-3} at 20 ^{0}C); g is the acceleration due to gravity (9,81 m s^{-2}); and h is the drop in air pressure across the core (Pa). The K_a values were multiplied by 10^{12} to convert the units from m^2 to μm^2.

Air-filled porosity ($m^3\ m^{-3}$) was calculated as:

$$\mathbf{E_a = E_t - O_v}\ ....\text{Eq.1.4}$$

where

$$\mathbf{E_t = 1- (P_b / P_s)}\ ....\text{Eq.1.5}$$

and E_a is the air-filled porosity ($m^3\ m^{-3}$); E_t = total porosity ($m^3\ m^{-3}$); O_v is the volumetric water content ($m^3\ m^{-3}$); P_b is the bulk density of the soil (kg m^{-3}) and P_s is the particle density which is usually assumed to be 2650 kg m^{-3} for most mineral soils. E_a, like O_v is a function of matric potential.

Soil macro, meso and micropores were investigated using the water retention curve and the capillary theory (Equation 1.6) that the amount of water retained in the soil is dependent upon the volume of the water filled pores. At saturation all of these pores are water filled (Hillel, 1998). The size of soil pore that is drained is related to the pressure below atmospheric (matric potential) of the soil water according to the capillary equation (Glinski and Stepniewski, 1983).

$$P = 2\gamma / r.\cos\alpha \text{ ....Eq. 1.6}$$

where P is the pressure below atmospheric (suction) (Pa), γ is the surface tension of water (Nm^{-1}), r is the upper limiting radius (m) of capillary pores that remain full of water (i.e. pores > r will drain) and α is the contact angle. In freely wetting soils the contact angle of water is normally equated to zero. The total porosity was divided into macropores (>29 μm diameter; air filled porosity at -10 kPa), larger mesopores (2.8 - 29 μm diameter; water drained between -10 and -100 kPa), smaller mesopores (0.2 - 2.8 μm diameter; water drained between - 100 and -1500 kPa) and micropores (<0.2 μm diameter; water filled pores at - 1500 kPa).

Roots were collected from a set volume of soil using a core ring (75 mm i.d. and height 50 mm). For each replicate, three cores were taken and bulked at each depth. Samples were taken at (0 - 15 cm, 15 - 30 cm, 30 - 45 cm and 45 - 60 cm) depth increments, depending on the rooting depth of the field being sampled. The soil was then washed off, roots collected and dried. A root length machine (Geotron) was then utilised to determine the cumulative root length for each sample. The results were expressed on a root density basis ($cm\ cm^{-3}$).

Penetrometer resistance was measured using a manual, hand held penetrometer, with design and dimensions based on the specifications from the American Society of Agricultural Engineering, 1973, (William, 1977). The cone angle was a standard 30^0 and the cross sectional area of the cone was $1.13 \times 10^{-4}\ m^2$. Penetrometer resistance was measured when the soil was at field capacity to add homogeneity to the sampling. Ten replicates were taken from each site.

The relationship between some of the measured properties was investigated and the significance determined using simple linear regression. The statistical program Genstat 5, version 4.1 was utilized.

4.3 Results

The root length density (Figure 4.1) at all four sites followed the same general trend. The annual ryegrass sites had the lowest densities and shallowest rooting depths, whilst kikuyu pastures had the highest densities at Brandkop, Lanark and Heidehof to a depth of aproximately15 cm. Root density was highest under native vegetation at Kenmore to a depth of 60 cm. The native vegetation also had the highest root density from approximately 15 to 60 cm at Brandkop and Heidehof. The root density decreased at all sites with depth.

The effect of subsoiling on root density was clear to a depth of 60 cm (Figure 4.2). As expected root density below the tines was greater than that between the tines, which in turn was greater than that in the adjacent unsubsoiled field. The effect of subsoiling on root length density was most pronounced close to the surface but rooting depth was also clearly increased.

Ryegrass pastures had the highest and kikuyu the lowest bulk densities in the 0 - 15 cm layers at both Lanark and Heidehof (Figure 4.3). However, at Brandkop and Kenmore values under both kikuyu and ryegrass pastures were higher than those under native vegetation. The bulk density values in the 0 - 15 cm layer ranged from an exceptionally low value of 0.86 Mg m^{-3} under native vegetation at Kenmore to 1.68 Mg m^{-3} under ryegrass pasture at Heidehof. Under kikuyu pasture at Heidehof and Kenmore and ryegrass pasture at Lanark and Kenmore bulk density was notably greater in the 15 - 30 than 0 - 15 cm layer. This is a possible indication of the presence or development of subsoil compacted layers. Again in the 15 - 30 cm layer, ryegrass pastures had the highest bulk density values at Lanark and Heidehof, whilst kikuyu pastures had similar high values to those under ryegrass at Brandkop and Kenmore.

As expected, total porosity generally showed the reverse trends to those for bulk density with land management (Figure 4.3 and 4.4). That is, in both the 0 - 15 and 15 - 30 cm layers, total porosity was lower under ryegrass than kikuyu pasture at Lanark and Heidehof (Figure 4.4). At Brandkop and Kenmore, porosity was considerably lower under pasture than native vegetation and it tended to be lower under kikuyu than ryegrass pasture.

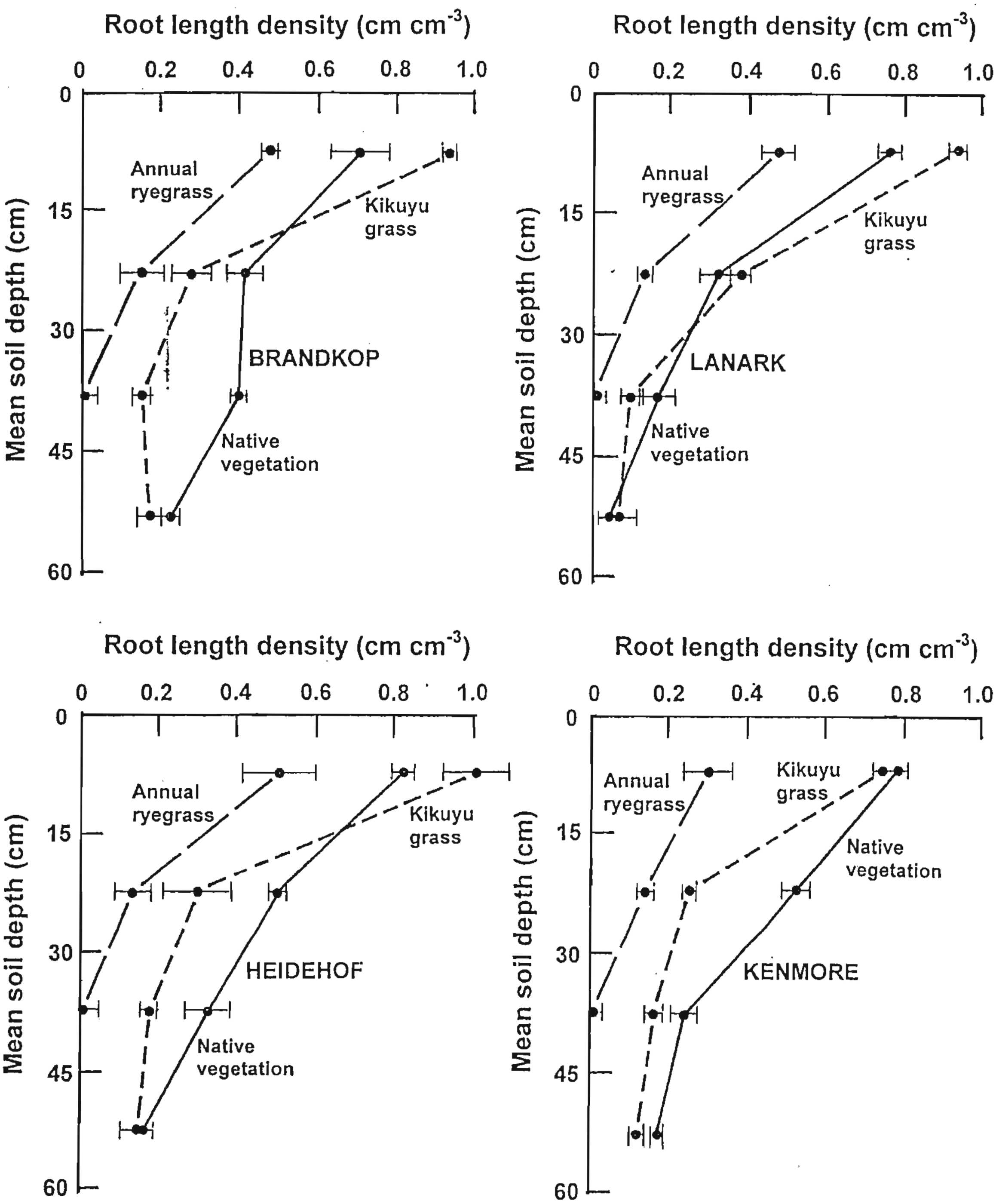


Figure 4.1 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on root density in the soil profile. Bars indicate ± standard error (S.E.) of the means.

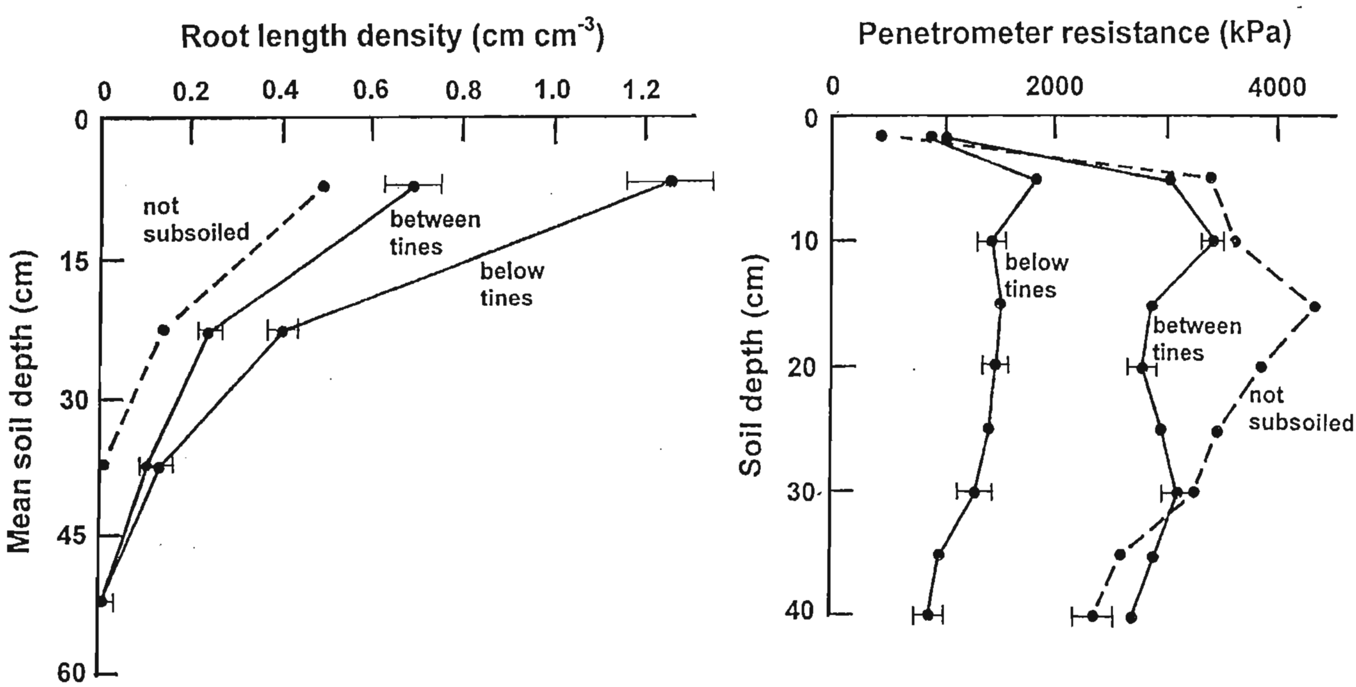


Figure 4.2 Effect of subsoiling an annual ryegrass pasture at Lanark on root density and penetrometer resistance in the soil profile sampled below and between the subsoiler tines. Results from an adjacent annual ryegrass field (see Figure 4.1) that had not been subsoiled are shown for comparison. Bars indicate ± standard error (S.E.) of the means.

The effects of subsoiling on bulk density and total porosity are shown in Figure 4.5. Below the tines, bulk density was decreased and porosity increased in both the 0 -15 and 15 - 30 cm layers. The difference in values for below and between the tines was more pronounced in the 15 - 30 than 0 - 15 cm layer. As expected, in the 0 -15 cm the highest bulk density occurred in the adjoining unsubsoiled field. However, in the 15 - 30 cm layer, bulk density was, in fact greater and total porosity less, between the tines than in the unsubsoiled field. This is presumably attributable to variability in density and porosity at this depth between the two adjacent fields.

Water retention curves for each of the sites are shown in Figure 4.6. in order to demonstrate the effect of site (i.e. soil type) on water retention, curves for the different sites are grouped according to land use. The soil at Kenmore (which had the highest clay content; see chapter 3) generally had the highest initial saturated water content and the smallest loss in water content with decreasing matric potential. By contrast, the very sandy soil at Brandkop showed the greatest change in water content with decreasing matric potential and it had the lowest water content at -100 kPa under each of the land uses.

For the 0 - 15 cm layer, pore size distribution is shown in Table 4.1. For each land use the lowest proportion of micropores (<0.2 μm diameter) occurred in the sandy soil at Brandkop whilst the greatest proportion occurred in the finer-textured soil at Kenmore. Land management also had substantial effects. At both Lanark and Heidehof, where annual ryegrass had a greater soil bulk density and lower total porosity than the kikuyu grass treatment, the proportion of macropores (>29 μm diameter), was surprisingly greater under ryegrass. At Heidehof and Kenmore, the proportion of macropores present was notably higher under native vegetation than other land uses. Macroporosity was notably low (<10 %) under ryegrass and kikuyu pasture at Kenmore and under kikuyu pasture at Lanark. At Brandkop, Lanark and Heidehof, the proportion of pores in the size class 0.2 - 2.8 μm diameter was notably higher under kikuyu grass than the other land uses. Calculation of pores size distribution in the 15 - 30 cm layer did not show any consistent changes due to land management and consequently the data is not presented.

The effect of subsoiling on water retention curves is shown in Figure 4.5. The saturated water content was higher below and between the tines than in the unsubsoiled field. Although both below and between tine values started with approximately the same saturated water content, there was a noticeably greater amount of readily available plant water (held between -10 and -100 kPa) below than between the tines in the 0 -15 cm layer. Calculation of pore size distribution in the 15 - 30 cm layer did not shown any desirable trends due to subsoiling but in the 0 -15 cm layer (Table 4.2) there was an increase in the percentage of macropores present below and between the tines, compared to unsubsoiled conditions. This was accompanied by a decrease in the proportion of mesopores (0.2 - 29 μm diameter) present.

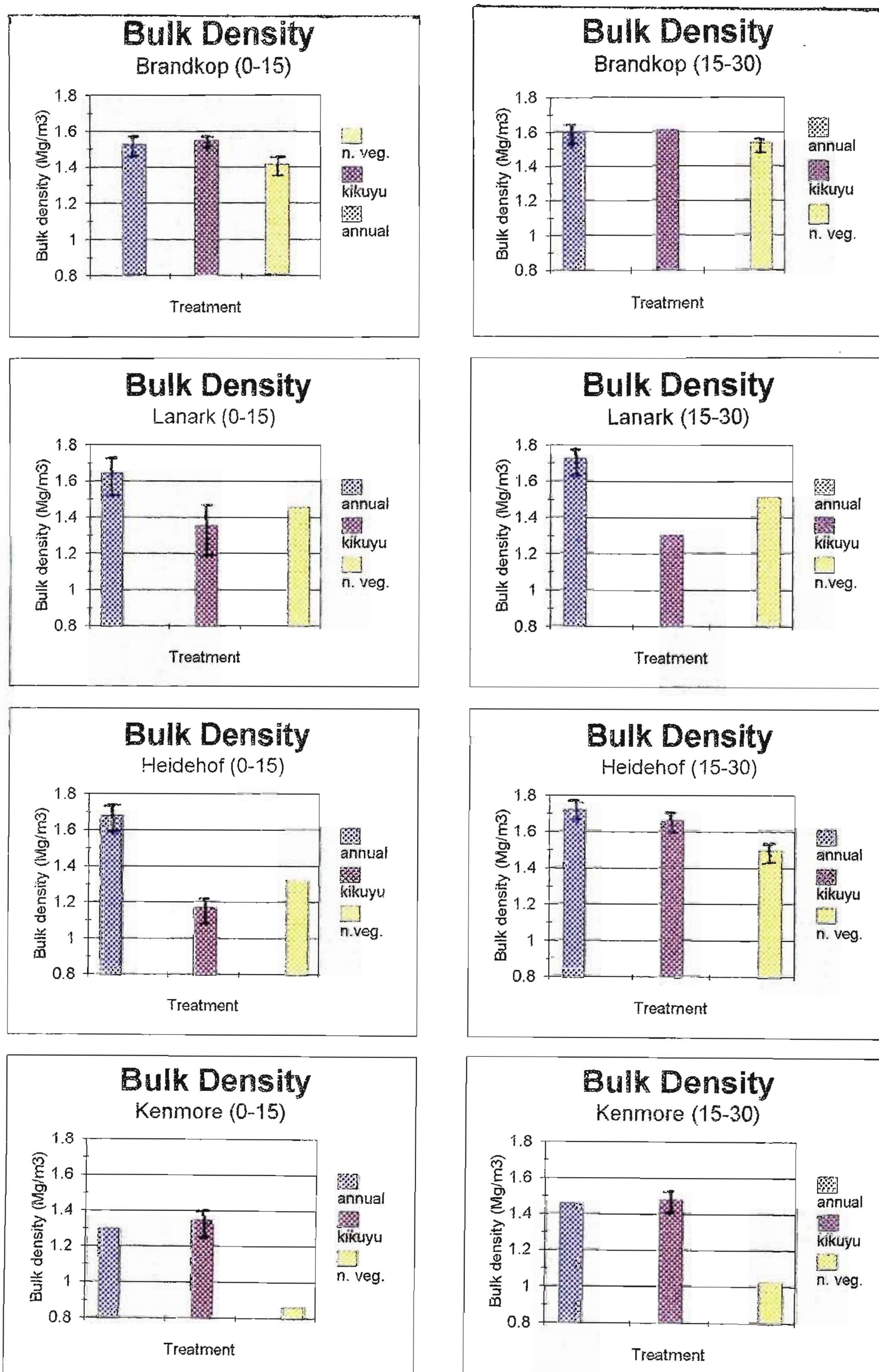


Figure 4.3 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on bulk density in two soil layers (0 - 15 and 15 - 30 cm). Bars indicate ± standard error (S.E.) of the means.

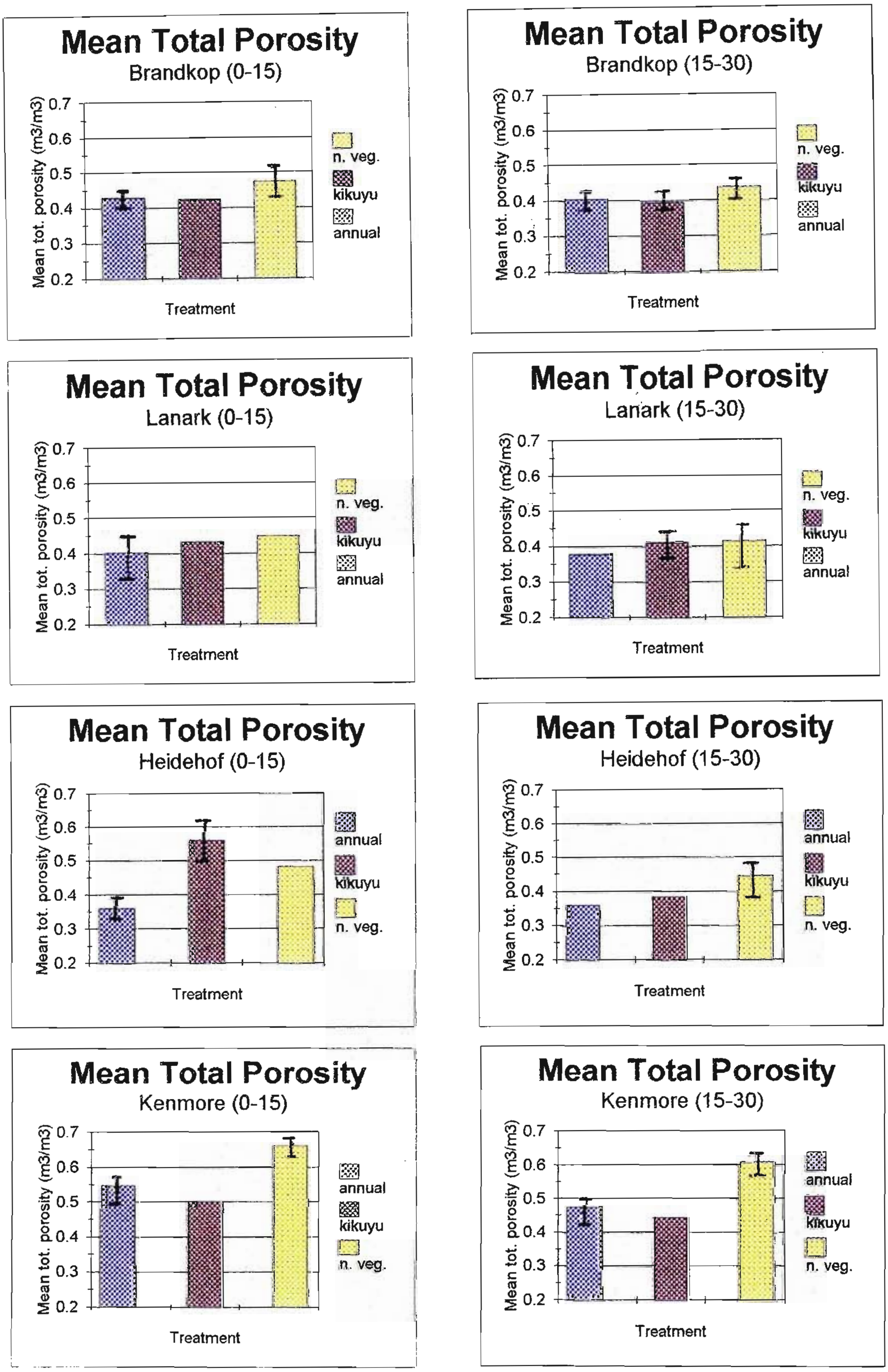
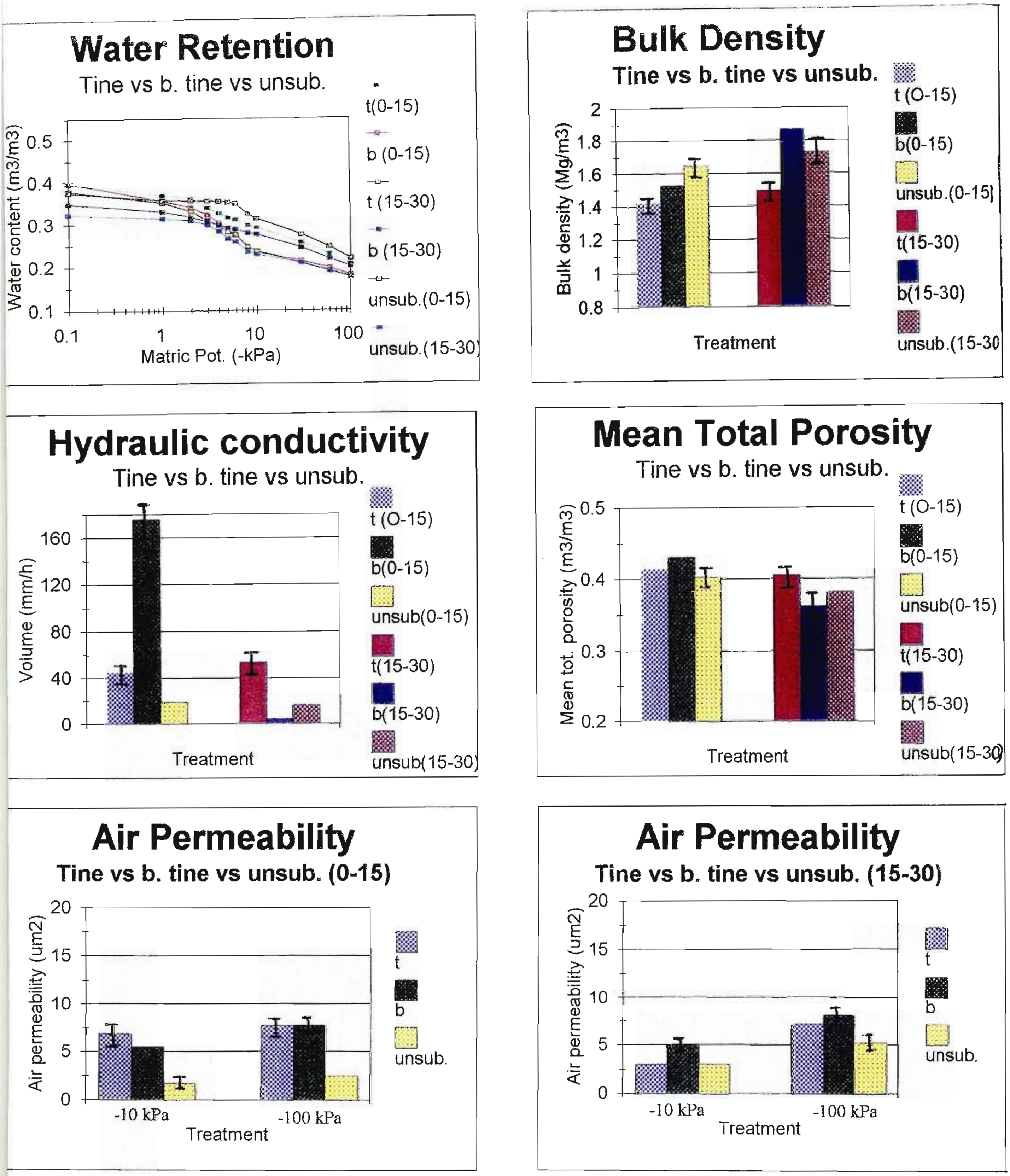


Figure 4.4 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on mean total soil porosity in two soil layers (0 - 15 and 15 - 30 cm). Bars indicate ± standard error (S.E.) of the means.



gure 4.5 Effect of subsoiling an annual ryegrass pasture at Lanark on bulk density, water tention, mean total soil porosity, air permeability and saturated hydraulic conductivity of soil mpled below the subsoiling tine (t) between (b) the tines or from the adjacent unsubsoiled field nsub.) in two soil layers (0 - 15 and 15 - 30 cm). Bars indicate ± standard error (S.E.) of the eans.

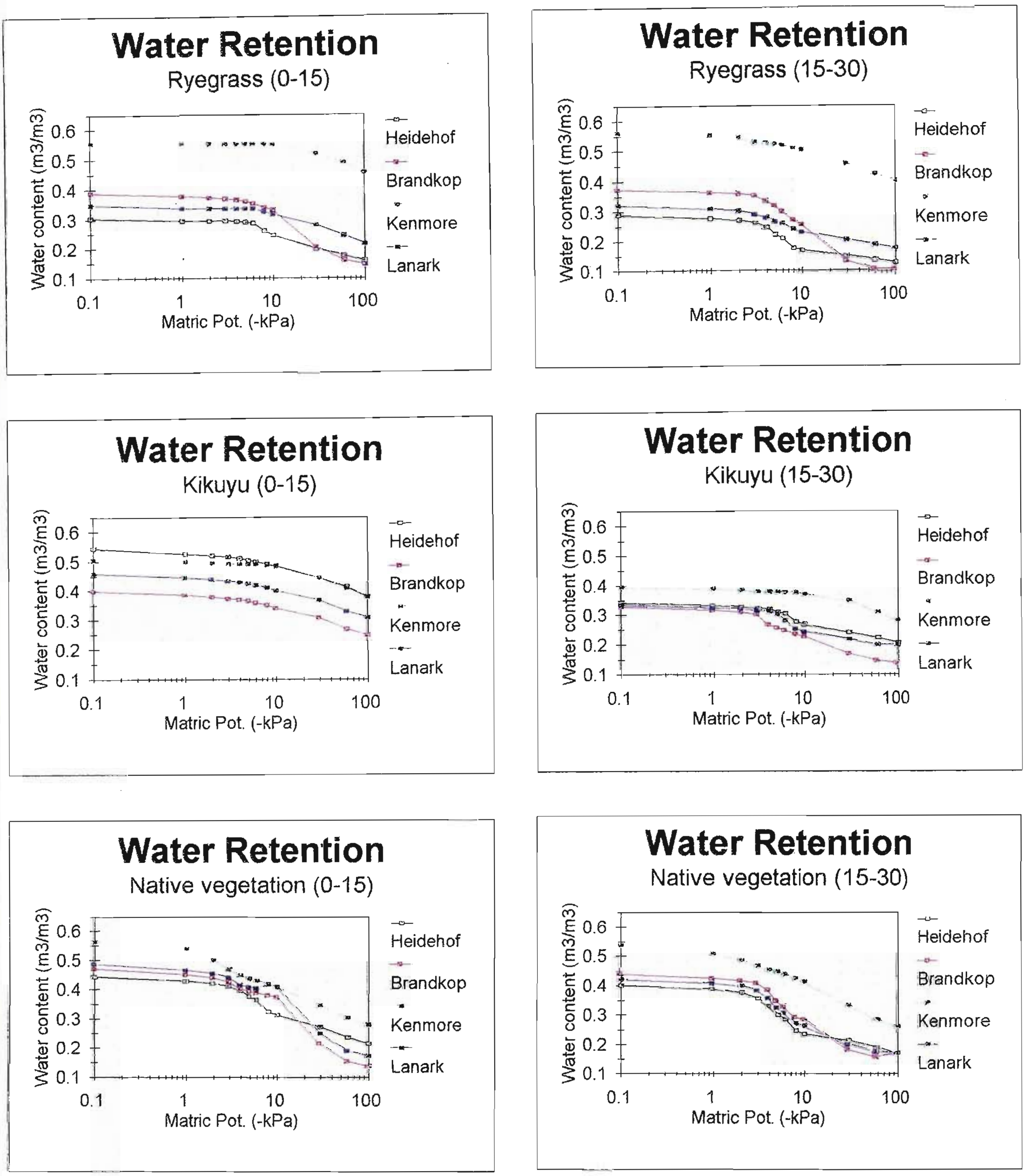


Figure 4.6 Water release curves for two soil layers (0 - 15 and 15 - 30 cm) at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) under annual ryegrass, permanent kikuyu pasture and native vegetation.

Table 4.1 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites on pore size distribution (%) in the 0 - 15 cm soil layer. Standard errors shown in parenthesis.

Site and land use	Micropores (<0.2 μm)	Mesopores (0.2 - 2.8 μm)	Mesopores (2.8 - 29 μm)	Macropores (>29 μm)
Brandkop				
Annual ryegrass	16 (0.33)	18 (0.76)	43 (0.44)	23 (0.96)
Permanent kikuyu	17 (0.45)	41 (0.94)	22 (0.34)	20 (0.54)
Native vegetation	16 (0.22)	13 (0.94)	50 (0.63)	21 (0.35)
Lanark				
Annual ryegrass	33 (0.87)	20 (0.57)	25 (0.54)	22 (0.56)
Permanent kikuyu	34 (0.33)	37 (0.22)	21 (0.33)	8 (0.20)
Native vegetation	30 (0.64)	7 (0.13)	51 (0.58)	12 (0.17)
Heidehof				
Annual ryegrass	26 (0.88)	19 (0.54)	24 (0.68)	31 (0.84)
Permanent kikuyu	18 (0.53)	49 (1.13)	19 (0.61)	14 (0.56)
Native vegetation	21 (0.33)	24 (0.11)	20 (0.28)	35 (0.37)
Kenmore				
Annual ryegrass	34 (0.87)	47 (0.23)	17 (0.97)	2 (0.21)
Permanent kikuyu	38 (1.02)	37 (0.88)	21 (0.52)	4 (0.57)
Native vegetation	31 (0.13)	11 (0.33)	19 (0.48)	39 (0.67)

As expected, air permeability was greater at -100 than -10 kPa (Figure 4.7). At Brandkop, Lanark and Kenmore it was greatest under native vegetation in both the 0 -15 and 15 - 30 cm layers. At Heidehof, an unusually high air permeability was measured under kikuyu pasture (0 - 15 cm layer) at -100 kPa suggesting extensive pore continuity in this layer (possibly due to root or earthworm channels). At all the sites, air permeability was similar or in most cases greater under kikuyu than ryegrass pasture. Saturated hydraulic conductivity (Figure 4.8) was greater under native vegetation than pasture at both depths at Brandkop, Lanark and Kenmore. At Heidehof it was larger under kikuyu pasture than native vegetation. Values were similar, or in most cases larger, under kikuyu than ryegrass pasture in both layers.

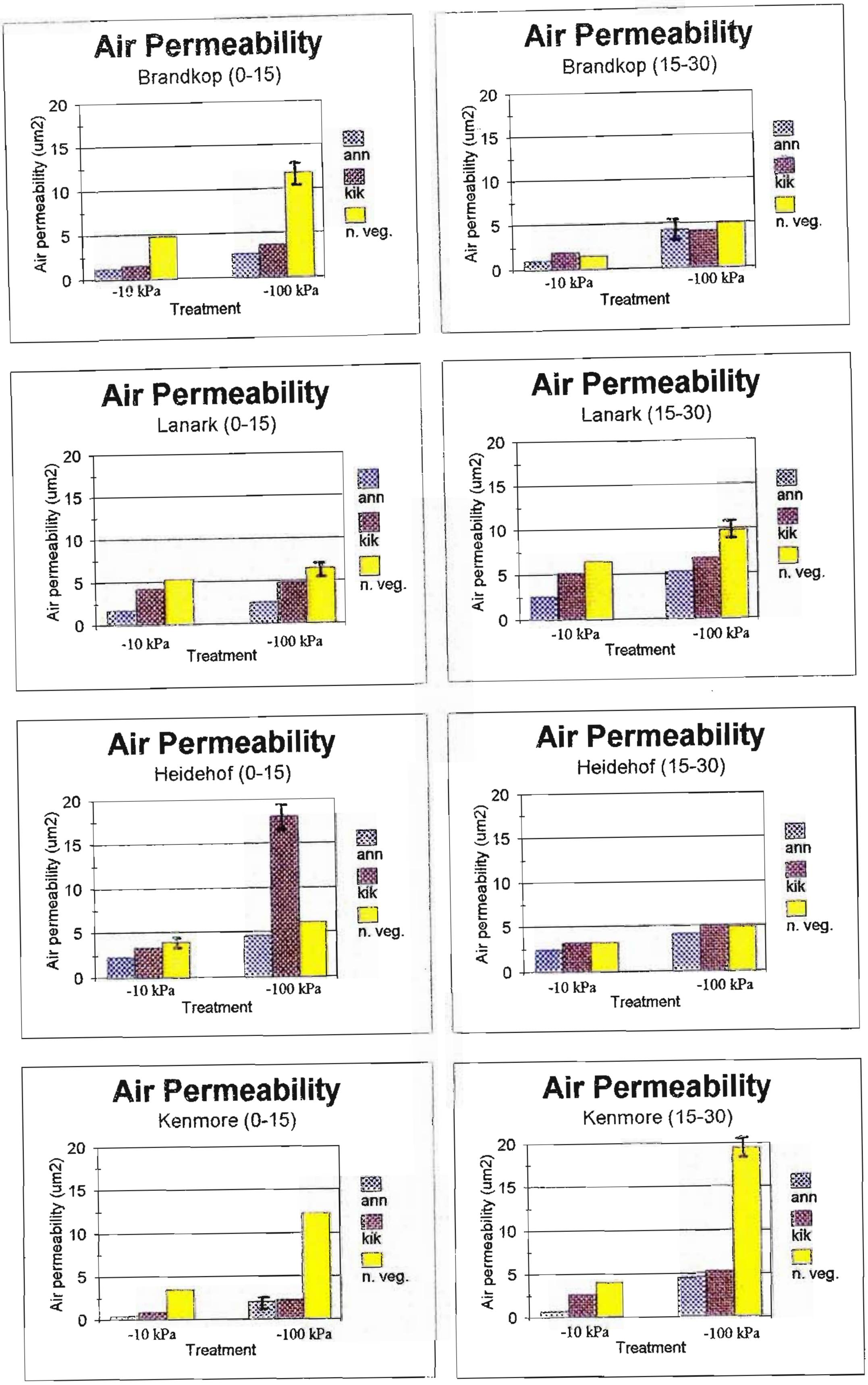
The effects of subsoiling greatly increased air permeability in the 0 - 15 cm layer both below and between the tines (Figure 4.5) and this was also the case at -100 kPa in the 15 - 30 cm layer. Saturated hydraulic conductivity was also greatly increased by subsoiling (Figure 4.5) in the 0 -15 cm layer below and between the tines.

Table 4.2. Effects of subsoiling an annual ryegrass pasture at Lanark on pore size distribution (%) in the 0 - 15 cm soil layer below and between the subsoiling tine and from an adjacent unsubsoiled field. Standard errors shown in parenthesis.

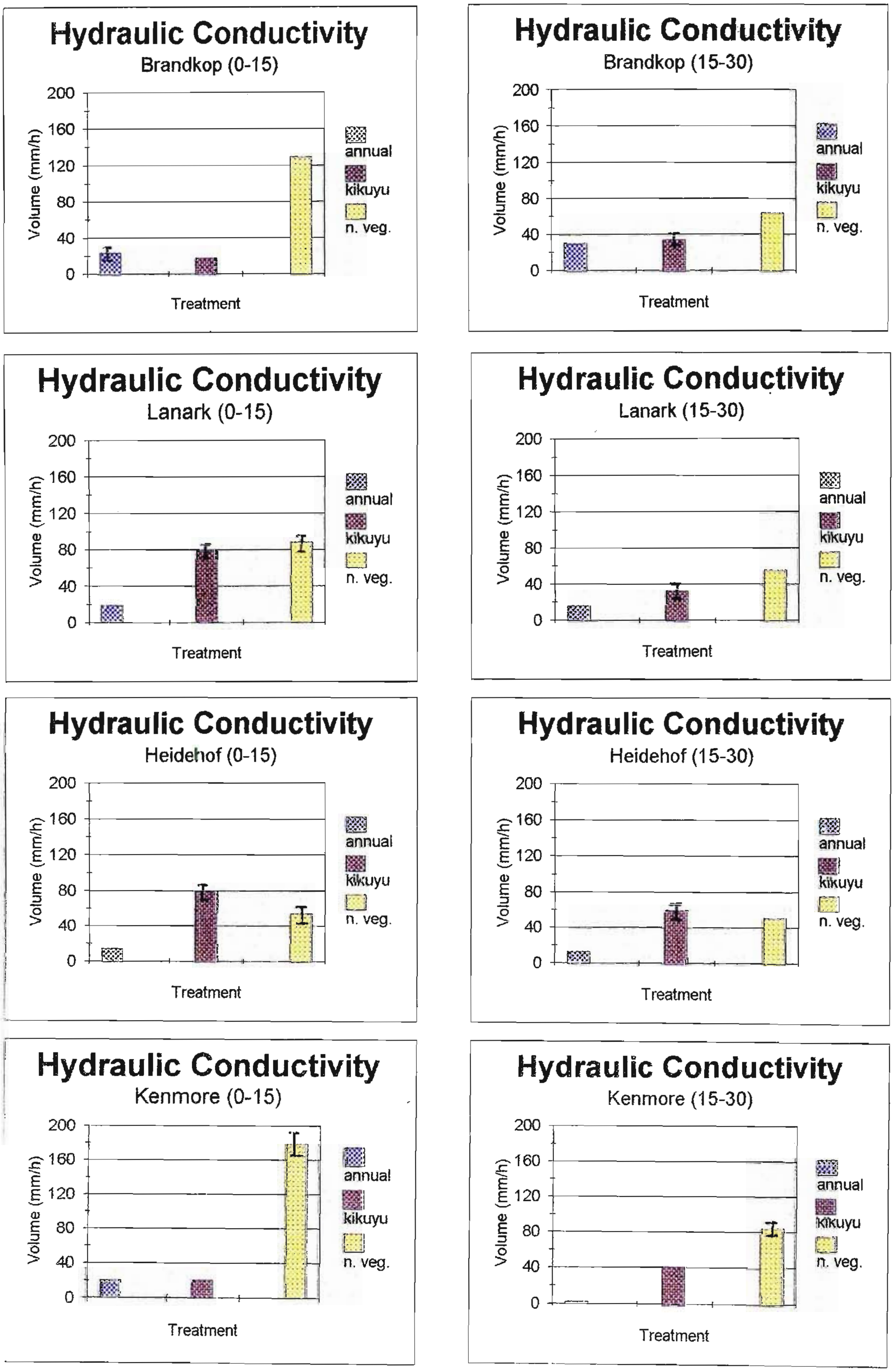
Treatment	Micropores (<0.2 μm)	Mesopores (0.2 - 2.8 μm)	Mesopores (2.8 - 29 μm)	Macropores (>29 μm)
Unsubsoiled	33 (0.57)	20 (1.02)	25 (0.89)	22 (0.91)
Below tines	34 (085)	15 (0.54)	21 (0.10)	30 (0.88)
Between tines	30 (0.12)	11 (0.34)	13 (0.77)	46 (0.57)

Penetrometer resistance down the profile (Figure 4.9) was highest under annual ryegrass at Lanark and Heidehof and under kikuyu pasture at Brandkop and Kenmore. Under ryegrass at Lanark and Heidehof, there was a peak of resistance in the 10 - 20 cm layer suggesting the presence of a compacted subsoil layer. At Brandkop and Kenmore resistance was lowest under native vegetation but at Lanark and Heidehof it was generally least under kikuyu pasture. Penetrometer resistance was considerably lower below the tines of the subsoiled field than in the adjacent unsubsoiled one (Figure 4.2). Between the tines, subsoiling had decreased resistance greatly in the 10 - 20 cm layer where a compacted layer was evident in the unsubsoiled profile.

Linear correlation coefficients between various soil physical properties are presented in Table 4.3. As shown in chapter 3, aggregate stability was significantly related to soil organic C content. It was also negatively related to bulk density and positively to total porosity and saturated water content. As expected, total porosity was strongly negatively correlated with bulk density and it was also correlated with saturated water content and hydraulic conductivity. Hydraulic conductivity was negatively correlated with bulk density and positively related to total porosity and air permeability. Root density was correlated with air permeability and hydraulic conductivity.



igure 4.7 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four arm sites (Brandkop, Lanark, Heidehof and Kenmore) on air permeabilityin two soil layers (0 1 5 and 15 - 30 cm). Bars indicate ± standard error (S.E.) of the means.



igure 4.8 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four rm sites (Brandkop, Lanark, Heidehof and Kenmore) on saturated hydraulic conductivity in two il layers (0 -15 and 15 - 30 cm). Bars indicate ± standard error (S.E.) of the means.

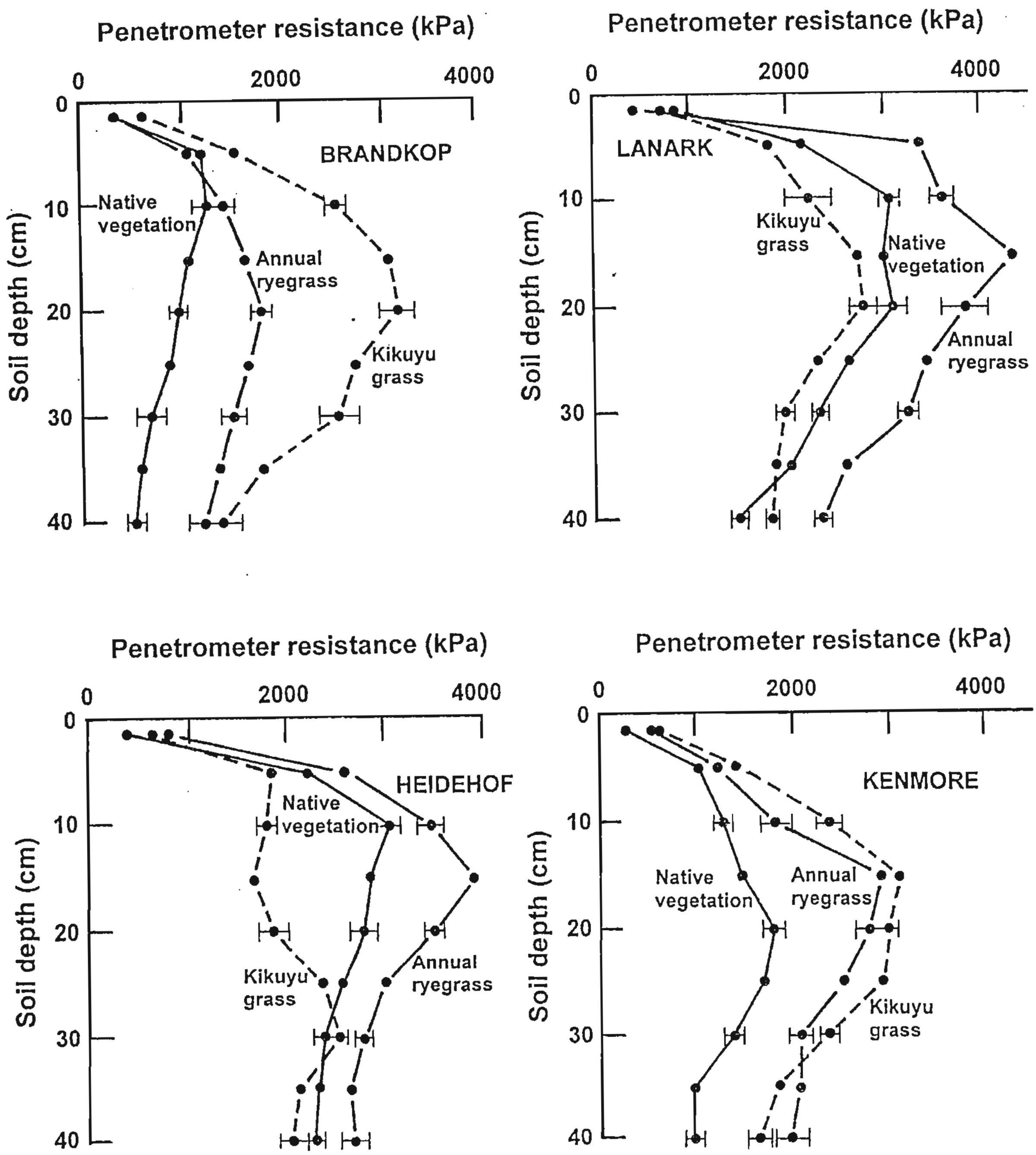


Figure 4.9 Effect of native vegetation, annual ryegrass and permanent kikuyu pastures at four farm sites (Brandkop, Lanark, Heidehof and Kenmore) on penetrometer resistance in the soil profile. Bars indicate ± standard error (S.E.) of the means.

4.4 Discussion

4.4.1 Root density

The dense, ramified, fine root system of grass has an important aggregating function in the form of an enmeshing effect, as do mycorrhizal fungal hyphae associated with the roots (Tisdall and Oades, 1979). The dense root system also supports a large microbial population in the rhizosphere which produces polysaccharide gums that help bind the soil particles together (Roberson *et al.*, 1991). The high root density and large below-ground biomass effects soil quality because of the associated effects on organic matter deposition, microbial activity in the rhizosphere, increased aggregate stability and cracking caused by soil shrinkage induced by plant uptake of water. In comparison with native vegetation and kikuyu pasture, ryegrass pastures were the shallowest rooting and had the lowest root density in the surface 45 cm. Several factors will have contributed to this. Firstly, kikuyu pastures and native vegetation are perennial and over time roots have penetrated to well below 60 cm at all the study sites. By contrast, ryegrass is sown annually so roots are concentrated near the surface. Ryegrass roots are also typically shallower and less vigorous than kikuyu roots (Anonymous, 1986). In addition, ryegrass pastures are generally irrigated and furthermore, the bulk density and penetrometer resistance are notably high under some of the annual ryegrass pastures. Irrigation, will minimize the need for roots to penetrate to depth in search of water while the high density of the surface soil will tend to inhibit root growth and penetration.

The development of a root system depends on the mechanical strength of the soil matrix and the number, size and geometry of the pores (Letey, 1985; Roseberg and McCoy, 1992). Roots that encounter pores their own size or larger tend to follow that pore rather than penetrate the soil ped (Wiersum, 1957; Roseberg and McCoy, 1992). It is surprising that although in previous studies root density has been shown to be negatively correlated with bulk density and positively correlated with total porosity (Lipiec and Simota, 1994), there was no correlation in the surface 15 cm in this study. However, that root density was not correlated with total porosity but was significantly correlated with air permeability and hydraulic conductivity suggests the importance of pore continuity rather than total porosity to root growth. An explanation for this may be that for roots to proliferate in these soils, cracks and other interconnected pores are required rather than isolated voids.

At Brandkop, Heidehof and Kenmore the roots under native vegetation were more dense in the 15 - 45 cm layer than under kikuyu pasture. This is attributable to the presence of deeper rooting shrubs and bushes (and trees at Kenmore) growing among the native grasses. At Lanark, however, the pattern of root density with depth was similar under native vegetation and kikuyu pasture.

4.4.2 Bulk density and total porosity

Bulk density is an extremely useful measurement and is often used to assess changes in soil structure (Blake and Hartge, 1986; Lobry de Bruyn and Kingston, 1997). Bulk density was negatively correlated with several of the measured soil physical properties namely; mean total soil porosity, saturated hydraulic conductivity, saturated water content, air permeability at -100 kPa, aggregate stability and organic C (Table 4.3). Thus an increase in bulk density (often caused by mechanical or animal traffic) has been shown to reduce soil porosity, saturated hydraulic conductivity, air permeability and overall crop yield (Unger, 1996). Soil bulk density can also increase naturally from causes other than traffic, such as raindrop impact and structural failure of soils with characteristically low aggregate stabilities (Unger, 1996).

The fact that there was no consistent effect of improved pasture or pasture-type on bulk density and total porosity reflects the complex interaction of factors that influence soil physical conditions. That is, whilst bulk density was least and total porosity greatest under native vegetation at Brandkop and Kenmore this was not the case at the two other sites. Similarly, although bulk density was greater and porosity less under ryegrass than kikuyu pasture at Lanark and Heidehof, the reverse tended to be the case at Brandkop and Kenmore.

Under ryegrass pastures, annual cultivation will have a substantial effect on physical properties. Immediately, following conventional tillage there is an increase in porosity and a decrease in bulk density (Roseberg and McCoy, 1992; Ahuja *et al.*, 1998). However, repeated conventional tillage results in a loss of soil organic matter and a decrease in soil microbial activity and aggregate stability (see chapter 3). As a result, structural failure can occur causing natural consolidation and the formation of a compact cultivated layer (Lal, 1993). This will have been aggravated by compaction caused by treading by grazing cows. The lower organic matter content under annual pastures will result in lower soil strength and resilience (McGarry, 1993) and compaction will occur more easily than under permanent pastures. In addition, in order to obtain adequate pasture growth, annual pastures are irrigated regularly and grazing when the soil is at or near field capacity will increase the likelihood of compaction occurring. The sandy composition of these soils will also, to some degree, be responsible as it has been shown that soils with high sand contents, (such as Brandkop, Lanark and Heidehof) are especially prone to the development of a dense zone (Awadhwal and Smith, 1990).

An accumulation of organic matter often tends to improve soil physical conditions (Haynes, 1995; Haynes a Naidu, 1997). Indeed in this study organic C content was positively correlated with aggregate stability, total porosity and air permeability at -100 kPa and negatively correlated with bulk density. However, correlations were not strong suggesting that other factors (e.g. compaction) were also important. For example, the dense root system, high organic matter content and high aggregate stability (see chapter 3) under kikuyu pastures was expected to be translated into lower bulk densities and greater total porosities. However, although bulk density was lowest under kikuyu pasture in the 0 -15 cm layer at Lanark and Heidehof, it did, in fact, tend to be highest at Brandkop and Kenmore. The main reason for this is likely to be compaction caused by high stocking rates particularly when pasture soils are wet (Mulholland and Fullen, 1991).

Under permanent pastures, macroporosity may be restored naturally due to shrinkage and cracking caused by water uptake by the grass, death of roots creating channels and the burrowing activity of earthworms which are usually numerous under permanent pastures (Blevins and Frye, 1993). Because of the lower organic matter content, lower root density and lower soil biological activity these restorative processes are less likely to be effective under annual pastures. Subsoil tillage may be required to create macroporosity under annual pastures.

Table 4.3 Linear correlation coefficients (r)[a] between various measures of bulk density, organic carbon, aggregate stability, air permeability, saturated water content, saturated hydraulic conductivity, root density, mean total soil porosity and penetrometer resistance in the surface 15 cm of the soil.

Soil property	Penetrometer resistance	Mean total soil porosity	Root density	Hydraulic conductivity	Saturated water content	Air perm. -100 kPa	Air perm. -10 kPa	Aggregate stability	Organic carbon
Bulk density	n.s	-0.95***	n.s	-0.70**	-0.80***	-0.55*	n.s	-0.58*	-0.70**
Organic carbon	n.s	0.59*	n.s	n.s	n.s	n.s	0.58*	0.68**	
Aggregate stability	n.s	0.59*	n.s	n.s	0.75**	n.s	n.s		
Air perm. -10 kPa	n.s	n.s	0.69**	0.68**	n.s	0.51*			
Air perm. -100 kPa	n.s	n.s	0.65*	0.69**	n.s				
Saturated water content	n.s	0.86***	n.s	n.s					
Hydraulic conductivity	-0.54*	0.59*	0.51*						
Root density	n.s	n.s							
Mean total soil porosity	n.s								

[a] Statistical significance shown: n.s Not significant, * P≤0.05, ** P≤0.01, *** P≤0.001.

4.4.3 Water retention and pore size distribution

Soil water retention is a basic property of the soil that regulates the storage and movement of water within the soil and ultimately plant water use (Chen and Wheater, 1999). It is sensitive to both the inherent properties of the soil and past management practices (Crawford *et al.*, 1995).The water retention curves characterise the relationship between soil matric potential and water content for a particular soil. The amount of water retained in the soil is dependent upon the volume of the water filled pores. At saturation all of these pores are water filled (Hillel, 1998). As the soil is subjected to a suction (matric potential) the soil pores drain according to the capillary equation (Equation 1.6). Accordingly, the larger pores drain first. The continued incremental decrease in matric potential leads to further displacement of soil water by air, in progressively smaller sized pores (Crawford *et al.*, 1995) and as a result the pore size distribution can be calculated (Table 4.2).

The retention of water is influenced by both the texture and structure of the soil (Cresswell *et al.*, 1992). Textural influences tend to dominate at lower matric potentials (Cresswell *et al.*, 1992). Sandy textured soils, (such as Brandkop) generally have higher bulk densities and lower porosities than soils with a greater content of clay (such as Kenmore) and therefore tend to drain at higher matric potentials. This was evident from the results (Figure 4.6) since the lowest water content at -100 kPa occurred at Brandkop under all land treatments. The initial saturated water content was the lowest only under the kikuyu pastures, thus indicating a fairly high macroporosity. Indeed, the macropore volume at Brandkop remained at about 20 % regardless of land use (Table 4.1) suggesting that texture was the main determinant of macroporosity. The greatest change in water content with changing matric potential was also evident at Brandkop so the soils there had the smallest amount of readily available plant water. Both these trends correspond with the sandy nature of the soil at Brandkop (see chapter 3). In more finely textured soils (such as that at Kenmore) the soil water is distributed more equitably between the inter-particle and intra-aggregate pore spaces (Schulze *et al.*, 1985). They have lower bulk densities in their natural state and a more even pore size distribution than sandy soils, which in turn, results in a lower moisture loss at higher matric potentials. This trend was shown (Figure 4.6) by the higher initial saturated water content and the smaller change or loss in water content with decreasing matric potential. It follows that Kenmore had the largest amount of readily available plant water. As expected, while the soil at Brandkop had the lowest proportion of micropores under each land use, the finer-textured soil at Kenmore tended to have the greatest proportion.

Although land use had little effect on pore size distribution in the 15 - 30 cm layer, substantial changes were noted in the surface 15 cm. The sizable increase in the proportion of 0.2 - 2.8 μm diameter pores induced by kikuyu grass at Brandkop, Lanark and Heidehof is presumably related to the considerable amount of soil organic matter accumulated under kikuyu at these sites (see chapter 3). An increase in the amount of colloidal organic matter present in these predominately sandy soils has induced an increase in the proportion of smaller mesopores present.

The increase in the percentage of macropores present under ryegrass, compared to kikuyu grass, at Lanark and Heidehof (Table 4.1) which accompanied the decrease in total porosity is, at first sight, surprising. However, cultivation generally results in loosening of the soil and an increase in macroporosity (Ahuja *et al.*, 1998). Whilst natural consolidation and/or compaction under annual ryegrass pastures causes an increase in bulk density and a decrease in total porosity, the percentage of total pore space occupied by macropores is still greater than under permanent kikuyu pasture.

Macroporosity is a useful indicator of aeration status of soils (Glinski and Stepniewski, 1983). Macropore volumes below 10 %, although often adequate for soil permeability (Carter, 1988), are usually considered sub-optimum for adequate aeration for plant growth (Ball *et al.*, 1988). Values below 10 % were recorded under annual ryegrass and kikuyu grass at Kenmore (2 and 5 % respectively) and under kikuyu grass at Lanark (8%). In accordance with this, lowest values for air permeability at both -10 and -100 kPa in the 0 -15 cm layer were encountered under ryegrass and kikuyu pastures at Kenmore.

4.4.4 Air permeability and saturated hydraulic conductivity

Air permeability is an indication of how permeable a medium is to the transfer of air and the higher the permeability the greater and easier the air exchange between the soil and atmosphere. Pore-geometric factors strongly influence soil air flow (Bear, 1972; Roseberg and McCoy, 1990) and include total porosity, pore size distribution, pore continuity, tortuosity and shape (Roseberg and McCoy, 1990). These properties are closely related to the matric potential of soil water, soil bulk density and soil structure (Stepniewski *et al.*, 1994). Water movement in soils of similar texture can vary widely, depending on soil structure. Large connected pores can conduct large amounts of water under both saturated and unsaturated conditions (Watson and Luxmoore, 1986; Roseberg and McCoy, 1992).

The fact that saturated hydraulic conductivity and air permeability were closely correlated reflects the fact that both properties are closely related to pore continuity (Roseberg and McCoy, 1990). Interestingly, total porosity was not significantly correlated with air permeability and only weakly correlated with hydraulic conductivity. That is, in the study soils, total porosity is not necessarily closely related to pore continuity and thus the capacity of the soil to transport air or water through it.

Changes in hydraulic conductivity and air permeability with treatment did not closely follow those for bulk density and total porosity. For example, values for hydraulic conductivity were, as expected, lower under ryegrass than kikuyu at Lanark and Heidehof but were also similar or lower at the other two sites even when total porosity tended to be higher under ryegrass. Similarly, air permeability was generally less under ryegrass than kikuyu pasture. This tendency for smaller hydraulic conductivity and air permeability under ryegrass, regardless of whether total porosity is higher or lower, is presumably related to a decrease in pore continuity under ryegrass compared to kikuyu pasture. Under permanent kikuyu pasture there will be many surface-connected pores running to depth arising from root channels (i.e. death of roots), cracks caused by drying and wetting and the activity of soil fauna (e.g. earthworms) (Haynes, 1995). By contrast, under annual ryegrass, natural consolidation of the cultivated layer and compaction by animals may cause breakdown and/or horizontal layering of soil peds resulting in the formation of isolated voids within the soil volume. In addition, the relatively sparse root growth and lack of turnover of a deep perennial root system will result in less formation of surface connected macropores. Similar findings were recorded by Roseberg and McCoy (1992). They observed that although tillage decreased bulk density, thereby creating greater total porosity in the cultivated layer, this did not automatically translate into higher air permeability. This was attributed to tillage reducing macropore stability and continuity.

With the exception of Hediehof, hydraulic conductivity and air permeability were greatest under native vegetation. The undisturbed soil under such vegetation had the roots of a variety of perennial species (grasses, bushes and sometimes trees) ramifying through it and also probably contains a sizeable soil faunal community. As a result, pore continuity within the soil volume allows for effective air exchange and water movement. Thus, regardless of whether the bulk density was less (e.g. Brandkop) or more (e.g. Lanark) than under kikuyu pasture, the hydraulic conductivity and air permeability is still greater under native vegetation.

4.4.5 Penetrometer resistance

The measurement of the soil's resistance to the insertion of a penetrometer is a secondary indicator of soil compaction and is not a direct physical measurement of any specific soil condition (William, 1977). Penetrometer resistance is greatly effected by both soil moisture content and texture (William, 1977). It does, however, provide the recording of easy and rapid measurements. In this study, penetrometer resistance in the 0 -15 cm layer was not significantly, or only poorly correlated with other soil physical properties (Table 4.3). Nonetheless, most of the substantial differences in penetrometer resistance between land uses occurred in the 10 - 30 cm layer (Figure 4.9). In these lower layers, changes in penetrometer resistance could be broadly related to changes in bulk density.

In accordance with the bulk density results, kikuyu pastures at Brandkop and Kenmore had the highest penetrometer resistance, indicating considerable compaction under kikuyu pasture. As expected from bulk density measurements the annual ryegrass pastures had the highest penetrometer resistance and kikuyu pasture the lowest at Lanark and Heidehof. The large penetrometer resistance in the 15 - 25 cm layers at Kenmore and particularly at Brandkop under kikuyu pastures are likely to be the result of compaction caused by treading by grazing cows particularly when the soil is wet. The greatest penetrometer resistance (>4000 kPa) was recorded in the 10 - 20 cm layer under annual pasture at Lanark and Heidehof. This is an indication of the presence of a subsoil compacted layer in these soils. This will have been generated by compaction caused by grazing cows, and more particularly, by formation of a "pan" at the depth of cultivation. Cultivation is generally carried out using a tractor-mounted rotary cultivator and when the soil is wet, smearing and compaction by the rotary blades will tend to occur at the depth of cultivation. Such cultivation occurs to the same depth, annually, and a subsoil compacted layer was identified visually by examination of the soil profile at both Lanark and Heidehof.

4.4.6 Effect of subsoiling

Subsoiling is a type of tillage that aims to loosen or break up a compacted soil layer without inversion or mixing (Spoor and Godwin, 1978; Holloway and Dexter, 1991; Harrison *et al.*, 1994) and create a network of interconnected pores. Subsoiling must, however, be done correctly in order to be effective. If it is done incorrectly it can set in motion a wide range of degradative processes including the deterioration of soil structure, and accelerated erosion (Lal, 1993). Various factors such as soil moisture content, depth and tine spacing are critical to the effectiveness of subsoiling (Haynes, 1995).

The effectiveness of subsoiling in breaking up the compacted layer can be seen from the results presented in Figure 4.2. Penetrometer resistance was decreased greatly below the tines and between the tines it was reduced, particularly in the 10 - 20 cm layer, where resistance was greatest in the adjacent unsubsoiled field. In addition it resulted in a decrease in bulk density and increase in total porosity in the 0 - 1 5 and 15 - 30 cm layers (below the tines). Although increases in total porosity were relatively small, substantial increases in hydraulic conductivity and air permeability were noted both below and between the tines. This suggests an increase in pore continuity as a result of subsoiling. Since subsoiling results in the creation of a network of interconnected cracks (pores) extending from the depth of loosening up to the soil surface, an increased pore continuity is to be expected. The creation of a network of interconnected pores through the soil enabled roots to proliferate in the surface 15 cm and also to penetrate to a greater depth. Visual observations of the soil profile revealed a concentration of root growth particularly in the soil volume where tines were pulled through the soil. Mechanical loosening has therefore effectively allowed root penetration into previously inaccessible horizons (Braim *et al.,* 1984; Greenwood, 1989; Harrison *et al.*, 1994). The pasture plants are therefore able to explore a larger volume of soil for both water and nutrients.

It is evident that at Kenmore, under annual ryegrass, a subsoil compacted layer had developed and that the condition was ameliorated by subsoiling. Avoiding the future development of such compacted layers should be an important management consideration under annual ryegrass pastures. Where compacted layers have developed subsoiling should certainly be considered.

4.5 Conclusions

it is important to recognise that soil physical conditions are very much influenced by management and that conditions in each field need to be appraised separately. In this study, examination of the soil physical conditions at four indicator farms demonstrated the complexity of factors that can influence soil structure and the complexity of interactions that exist between various measured physical parameters.

The most dramatic differences between annual ryegrass and permanent kikuyu pastures observed in this study were that root densities in the surface 30 cm layers were considerably less under ryegrass and rooting depth was also less. A consequence of this will be lower organic matter returns to the soil under annual than permanent pasture. In general, bulk density in the 0 - 15 and 15 - 30 cm layers was considerably greater, and total porosity correspondingly smaller, under ryegrass pasture than under native vegetation. Similarly, air permeability at both -10 and -100 kPa and saturated hydraulic conductivity, were lower under annual pasture than the native vegetation. Values for kikuyu pastures were variable, some tending to be similar to those for native vegetation, some similar to those for ryegrass pastures and some intermediate.

It is evident that the loss of soil organic matter and aggregate stability under annually cultivated ryegrass pasture can result in natural consolidation of the soil and formation of a dense surface (0 - 30 cm) layer. Consolidation may well be exacerbated by compaction caused by treading since the lower organic matter content will leave the soil less resilient to compacting forces. Nevertheless, in several cases bulk density and total porosity were similar under kikuyu and ryegrass pastures and at two of the sites penetrometer resistance was greater under kikuyu than ryegrass pasture. This suggests that compaction has also occurred under heavy grazing of permanent kikuyu pastures despite their higher organic matter content and greater aggregate stability. Natural recovery from such compaction through reformation of macropores via root channels, cracking and the burrowing activities of earthworms is, however, likely to be much more effective under permanent than annual pastures. Ameliorative actions such subsoiling may therefore be necessary especially under annual ryegrass pastures. The disruptive effect of annual cultivation on the pore continuity was evident from the substantial decreases in air permeability and saturated hydraulic conductivity that occurred under ryegrass compared to kikuyu pastures.

It is clear that the establishment of annual ryegrass, and to a lesser extent permanent kikuyu pastures, has generally resulted in an increase in bulk density and decrease in mean total soil porosity, air permeability, saturated water content, saturated hydraulic conductivity and readily available plant water. Such changes generally occur during compaction and can restrict root development, inhibit air and water movement and thus decrease the overall plant growth and production. The lack of mechanical and animal traffic under native vegetation has resulted in lower bulk densities, less disturbance to the soil pores and their continuity, particularly the macropores, and therefore the maintenance of generally better soil physical condition than under cultivated pastures.

In this study, subsoiling an annual ryegrass pasture was shown to be effective in reducing penetrometer resistance in the 10 - 20 cm layer (where a subsoil compacted layer had been identified). It also increased pore continuity (as evaluated by hydraulic conductivity and air permeability) and greatly increased root density and rooting depth. Before subsoiling is implemented, existence of a subsoil compacted layer needs to be confirmed and for it to be effective factors such as soil water content, depth of subsoiling and tine spacing need to be optimised. In similar situations, subsoiling is, however, likely to have similar effects to those observed here. Longer-term studies need to be carried out to examine the subsequent effects on pasture yields and thus economic viability of such an operation. In addition, subsoiling under permanent kikuyu pastures where subsoil compaction has developed, may also be warranted.

CHAPTER 5

A SURVEY OF THE SOIL AND PLANT NUTRIENT STATUS OF ANNUAL AND PERENNIAL PASTURES IN THE TSITSIKAMMA REGION

5.1 Introduction

Intensive pastures form a key component of animal production on many farms in South Africa, but animal performance is often below expectations (Miles *et al.*, 1995). Dairy farms consist of a complex "soil-plant-animal" ecosystem which is constantly modified by the activities of man and his management. A first step in balancing a pasture-based ration is to have an estimate of the levels of various nutrients in pasture and a knowledge of how these change with environment (including management) and plant growth (Miles and Tainton, 2000). Quantitative estimates of dietary requirements for energy, protein, minerals and vitamins are necessary in order to calculate the amount of pasture (and supplements) required for a specified level of performance (Holmes and Wilson,1987). In order to provide appropriate supplementation of dairy cows on pasture it is, however, necessary to have a clear knowledge of the nutrients available from the pasture base (Fulkerson *et al.*, 1998; Miles and Tainton, 2000). This requires the generation of a reliable and comparable data base and ensuring homogeneity of sampling and analysis.

The quantity of a nutrient element required by either plants or animals depends on its metabolic function and varies widely from element to element (Whitehead, 2000). There have been various quantifications of recommended or critical levels of nutrients in herbage for adequate pasture nutrition. These do, however, differ appreciably from the critical concentrations needed in feed to provide adequate nutritional requirements for grazing dairy cows. Imbalances or marginal mineral deficiencies can reduce growth, reproduction or health in ruminants, particularly dairy cows, because of their high demands of pregnancy and lactation (Holmes and Wilson,1987).

Although, for most elements, only a small proportion of the total soil nutrient content is immediately available for plant uptake, there is sometimes a clear relationship between the concentration of a nutrient element in the soil and the growth of plants or health of livestock (Whitehead, 2000).

These nutrient elements are often categorized into macro and micro nutrients, but the categories and importance do, to some extent differ between plants and animals (Whitehead, 2000). There are also important interactions or ratios between nutrients which can have far reaching consequences in terms of ruminant health.

The purpose of this study was to survey the soil and herbage nutrient status on dairy farms in the Tsitsikamma region. By this method, serious deficiencies, oversupplies or imbalances of nutrients can be identified and subsequently rectified. Forty farms were chosen and at each, a permanent kikuyu and annual ryegrass pasture was sampled. Extractable soil nutrients and herbage nutrient content were measured and values related to one another and to the nutritional requirements of both grass plants and grazing dairy cows.

5.2 Materials and Methods

Herbage and soil samples were taken from fields under annually cultivated perennial ryegrass (*Lolium perenne*) and permanent kikuyu (*Pennisetum clandestinum*) pastures from dairy farms in the Tsitsikamma region. In relation to the regions described in chapter 3, 15 fields were in region 1 (Groenkop soil form), (Soil Classification Working Group, 1991), 15 in region 2 (Cartref soil form) and 10 in region 3 (Kroonstad soils). The herbage samples were collected randomly (as close to the fourth leaf stage as possible) from three randomly chosen replicate plots (100m^2) each. They were sampled using a "grab" technique, in a manner intended to simulate grazing. The samples from each plot were bulked, oven dried at 70^{0}C, ground to a suitable particle size (<1mm). They were analysed for Ca, Mg, K, Na, P, Zn, Cu, Mn, B, N and S, according to the analytical methods of the Cedara plant laboratory (Riekert and Bainbridge, 1998). Ground plant tissue was dry ashed at 450 ^{0}C overnight, the residue shaken up in 1M HCl and Ca, Mg, K, Na, Zn, Mn and Cu in extracts were analysed by atomic absorption spectrophotometry, P by the molybdenum blue method and B by the Azomethine-H method. The N and S content of tissue was analysed using a LECO C/N/S analyser.

The soil samples were also collected from the replicate plots within each field. Twenty five random soil samples were taken to a depth of 10cm from each plot using a Beater tube auger (25mm inner diameter). Samples from each plot were bulked, air-dried and sieved (<1mm). Soil samples were analysed by routine soil testing methods at the Kwazulu-Natal Department of Agriculture Cedara laboratory as described by Manson *et al.* (1993). Exchangeable acidity and exchangeable Ca and Mg were extracted with 1M KCl (1 : 10; soil : solution ratio for 10 minutes) and pH was also measured on this extract using a glass electrode. Exchangeable K and extractable P, Zn and Mn were extracted with AMBIC reagent (0.025M NH_4HCO_3, 0.01M NH_4F, 0.01M ethalinediaminetetraacetic acid at pH 8.0) using a 1 : 10 soil : solution ratio for 10 minutes. In the extracts, Ca, Mg, K, Mn and Zn were analysed by atomic absorption spectrophotometry and P by the molybdenum blue method. Organic C content was estimated by near infrared spectroscopy using an NIR analyser.

Because of the very high concentrations of extractable P measured in many of the fields in the 0 -10 cm layer, six fields with extractable P values greater than 50 mg kg^{-1} were resampled to a depth of 80 cm to investigate the vertical distribution of P in the profiles. The six fields, two from each region under kikuyu grass pasture, were sampled from the three randomly chosen plots (see above) and five samples to a depth of 80 cm were taken using a Beater tube auger (25 mm inner diameter). Samples were divided into the 0 - 10, 10 - 20, 20 - 40, 40 - 60 and 60 - 80 cm layers and bulked to give three replicates per field. Extractable P was measured as described above.

5.3 Results

5.3.1 Soil properties

Soil analysis data is presented in Table 5.1 and Figures 5.1, 5.2, 5.3 and 5.4 on a mass basis (i.e. mg kg^{-1}) as is the normal international convention. The laboratory at Cedara Research Station reports it's data on a volume basis (i.e. mg L^{-1}) and the data, presented in this way, along with the density of the <1mm sieved samples, are presented in Appendix 1.

The mean, standard error and range of values for the measured soil properties are presented in Table 5.1 for the three regions of the study area. For both kikuyu and ryegrass pastures, organic C and exchangeable Ca, Mg and K were generally higher in region 3 than in regions 1 and 2. Mean values for these measurements were also higher under kikuyu than ryegrass pastures. There were no discernable differences between regions 1, 2 and 3 for pH, exchangeable acidity and extractable P, Zn and Mn. Extractable P values were generally very high and tended to be higher under kikuyu than ryegrass pastures. For example, mean values for regions 1, 2 and 3 were 73, 97 and 88 mg P kg^{-1} respectively for kikuyu pastures and 44, 54 and 73 mg P kg^{-1} respectively for ryegrass pastures.

Because there were few differences in soil nutrient status between regions, soil test values for the three regions were pooled in order to investigate the frequency distribution of measured values. The frequency distribution of values for organic C, pH, exchangeable acidity and extractable P under kikuyu and ryegrass pastures is shown in Figure 5.1. Organic C (and thus the organic matter) content of the soil was generally high under kikuyu pastures and values were distinctly skewed to the right (Figure 5.1). Values ranged from 20 - 90 g kg^{-1} and were most frequently between 50 and 60 g kg^{-1}. By contrast, values for annual ryegrass pastures were generally lower, skewed to the left and ranged from 10 - 80 g kg^{-1}. The majority of the values were in the 20 - 30 g kg^{-1} range, which was about half of that observed for the kikuyu pastures.

The $pH_{(KCl)}$ values (Figure 5.1) had a notably larger range of values under annual ryegrass than permanent kikuyu pastures. pH values were generally higher under permanent kikuyu than annual ryegrass pastures. For example, 44 % of the fields under ryegrass had a pH less than 4.8, whilst this was only the case for 13 % of the fields under kikuyu pasture. The pattern of frequency distribution for exchangeable acidity was broadly similar under kikuyu and ryegrass pasture. Nevertheless, as expected from the lower pH values for ryegrass, 15 % of exchangeable acidity values for ryegrass were > 1.5 m $mol_c kg^{-1}$ whilst for kikuyu pasture the equivalent value was only 7 %.

Extractable P levels were generally high in both the annual ryegrass and the permanent kikuyu pastures (Figure 5.1). Indeed, most soils had values well above the critical P range for pastures, (16 - 25 mg kg^{-1}; Manson *et al.*, 1993). Over 90 % of kikuyu and 58 % of ryegrass pastures had values above 40 mg kg^{-1} (over 50 mg kg^{-1} is considered very high for P). Values under ryegrass pastures were skewed to the left, with the majority (68 %) of the fields having values in the 20 - 60 mg kg^{-1} range, whereas 70 % of the fields under kikuyu pastures were above 60 mg kg^{-1}.

Ambic P concentrations were at or above 25 mg P kg^{-1} to a depth of 40 cm in fields 1, 2, 3, 4 and

5 (Figure 5.2). Extractable P levels in soils in the study area under native vegetation are typically low, ranging from about 3 to 9 mg P kg^{-1}. Elevated levels of P were noted to 80 cm at sites 2 and 3 and to 60 cm at sites 4 and 5.

Exchangeable Ca, Mg and K were all generally higher under kikuyu than ryegrass pastures (Figure 5.3). It is evident from Figure 5.3 that for these exchangeable cations the distribution of values tends to be skewed towards the left under ryegrass pasture. The recommended Ca range for pastures is 500 - 1500 mg kg^{-1} (Manson *et al.*, 1993) and while 85 % of the kikuyu pastures had contents greater than 500 mg kg^{-1}, for ryegrass pastures the corresponding value was only 47 %. The recommended exchangeable Mg and K ranges for pasture growth are between 100 and 150 mg kg^{-1} (Manson *et al.*, 1993). All values under kikuyu pastures exceeded 100 mg kg^{-1} but under ryegrass 28 % of exchangeable Mg levels and 56 % of exchangeable K levels were below this value.

The above trends were also shown for total exchangeable cations (Ca^{2+}, Mg^{2+} and K^{+}) levels (Figure 5.3). Firstly the kikuyu pastures had a far greater range of 30 - 240 $mmol_c\,kg^{-1}$, compared with 0 -120 $mmol_c\,kg^{-1}$ for ryegrass and secondly the ryegrass results were skewed to the left with 82 % of the ryegrass but only 32 % of kikuyu fields having values below 60 $mmol_c\,kg^{-1}$.

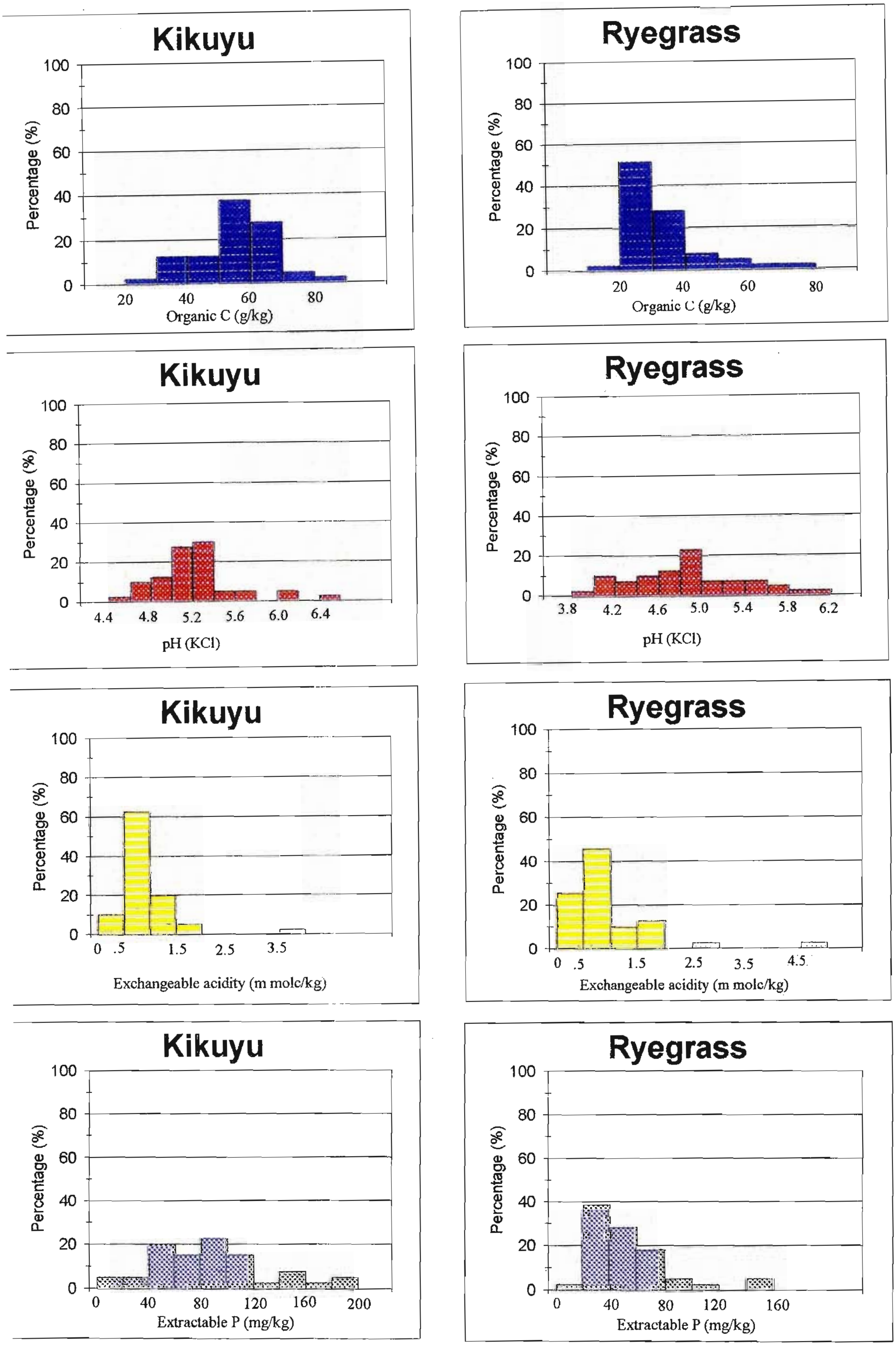
Whilst for ryegrass fields extractable Zn and Mn levels were concentrated in the 0 - 5 mg kg^{-1} range, under kikuyu pastures there was a much greater spread of values (Figure 5.4). For example, 92 % of ryegrass and only 37 % of the kikuyu fields had values below 10 mg kg^{-1} while for Mn, 96 % of ryegrass and 80 % of kikuyu fields had values below that level. It is recommended that the extractable Zn level should be above 1.5 mg kg^{-1} (Manson *et al.*, 1993); accordingly there are very few fields under either kikuyu or ryegrass that require Zn applications. A lower limit for extractable Mn has not yet been set although the upper limit, above which toxicities can occur in plants is about 500 - 1110 mg kg^{-1} (MacNicol and Beckett, 1985; Whitehead, 2000). Concentrations of Mn in leaf tissue were adequate (see below) suggesting that neither deficiencies nor toxicities of this nutrient were prevalent.

Table 5.1 Mean soil nutrient content, standard error and range of values for soils under kikuyu and ryegrass pasture in the three regions of the Tsitsikamma.

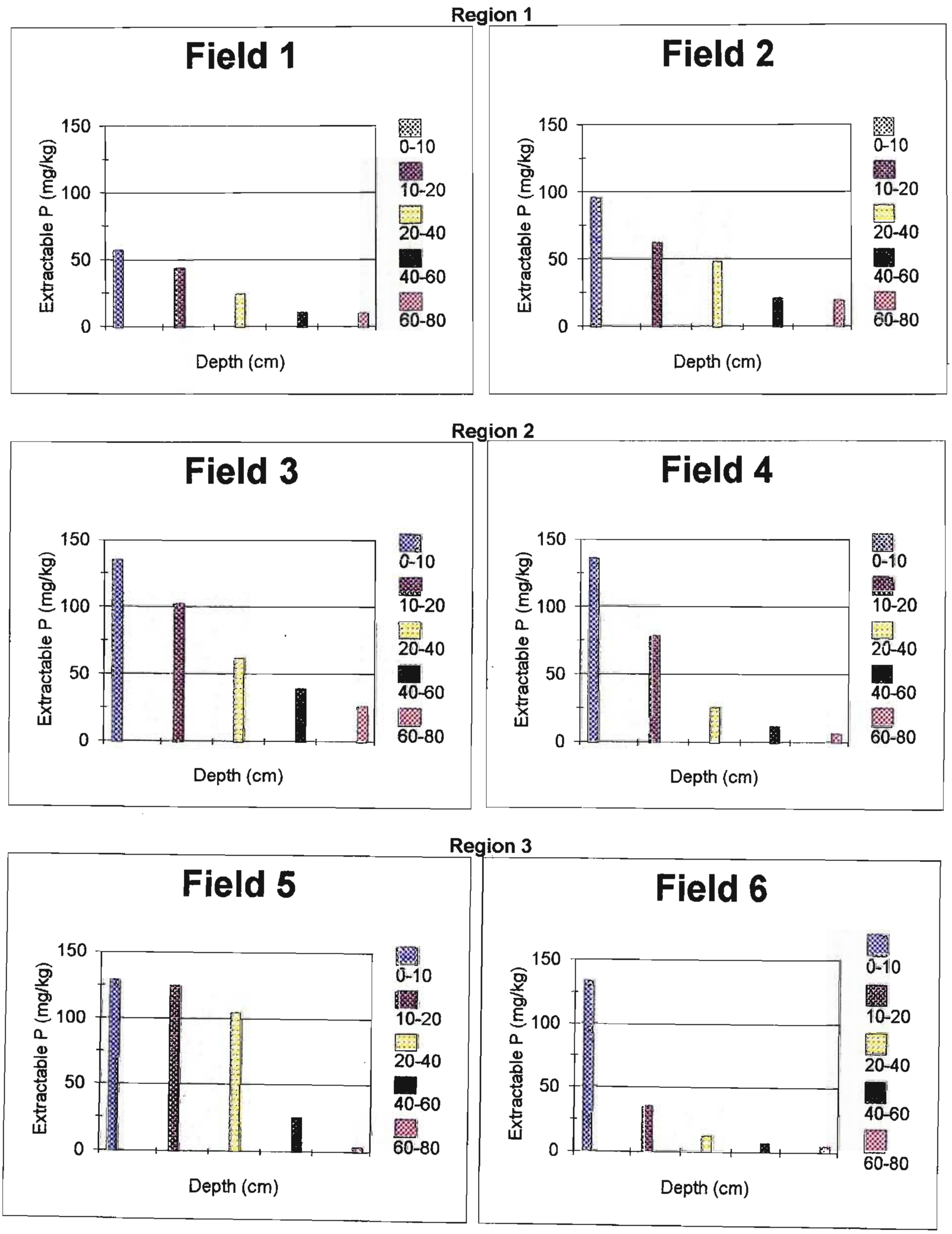
Region 1	Kikuyu				Annual			
Soil Nutrient	Mean	Std Error	Min	Max	Mean	Std Error	Min	Max
Organic C (g/kg)	51.014	2.705	29.838	63.917	29.291	1.506	17.600	36.719
pH$_{(water)}$	5.296	0.097	4.710	6.100	4.988	0.145	4.060	6.040
Exchangeable acidity (mmol$_c$ kg^{-1})	0.75	0.05	0.45	1.30	0.75	0.10	3.10	1.62
Extractable P (mg/kg)	72.510	7.289	20.168	115.888	44.288	6.248	19.491	107.031
Exchangeable Ca (mg/kg)	694.535	61.910	433.898	1,293.684	483.247	50.783	202.174	860.909
Exchangeable Mg (mg/kg)	273.734	31.212	149.194	633.684	123.209	14.833	53.623	229.060
Exchangeable K (mg/kg)	207.878	21.941	104.673	401.246	101.895	8.993	57.949	172.131
Total exchangeable cations (mmol$_c$ kg^{-1})	65.91	6.00	47.13	129.79	38.92	37.80	18.12	65.91
Extractable Zn (mg/kg)	11.184	1.544	3.874	22.243	4.536	0.721	1.783	11.639
Extractable Mn (mg/kg)	4.689	0.724	0.840	10.309	3.438	0.584	1.538	10.400
	no. =15				no. = 15			

Region 2	Kikuyu				Annual			
Soil Nutrient	Mean	Std Error	Min	Max	Mean	Std Error	Min	Max
Organic C (g/kg)	54.232	2.694	34.884	69.231	29	1.51	21.212	46.087
pH$_{(water)}$	5.103	0.056	4.68	5.44	4.629	0.136	3.91	5.82
Exchangeable acidity (mmol$_c$ kg^{-1})	1.03	0.1	0.57	1.84	1.29	0.31	0.24	4.75
Extractable P (mg/kg)	97.239	11.066	12.403	186.458	54.723	5.182	26.891	88
Exchangeable Ca (mg/kg)	766.056	79.316	348.837	1415.385	403.475	28.559	244.167	583.478
Exchangeable Mg (mg/kg)	299.655	29.482	130.233	527.473	98.508	7.814	51.667	140.517
Exchangeable K (mg/kg)	285.226	33.549	120.93	560.544	98.452	15.659	34.409	245.867
Total exchangeable cations (mmol$_c$ kg^{-1})	74.86	7.00	33.41	129.56	33.32	2.15	22.73	49.83
Extractable Zn (mg/kg)	18.427	3.887	5.648	56.042	4.359	0.456	1.642	8.534
Extractable Mn (mg/kg)	13.211	4.055	1.77	51.02	4.029	0.57	1.55	9.449
	no. = 15				no. = 15			

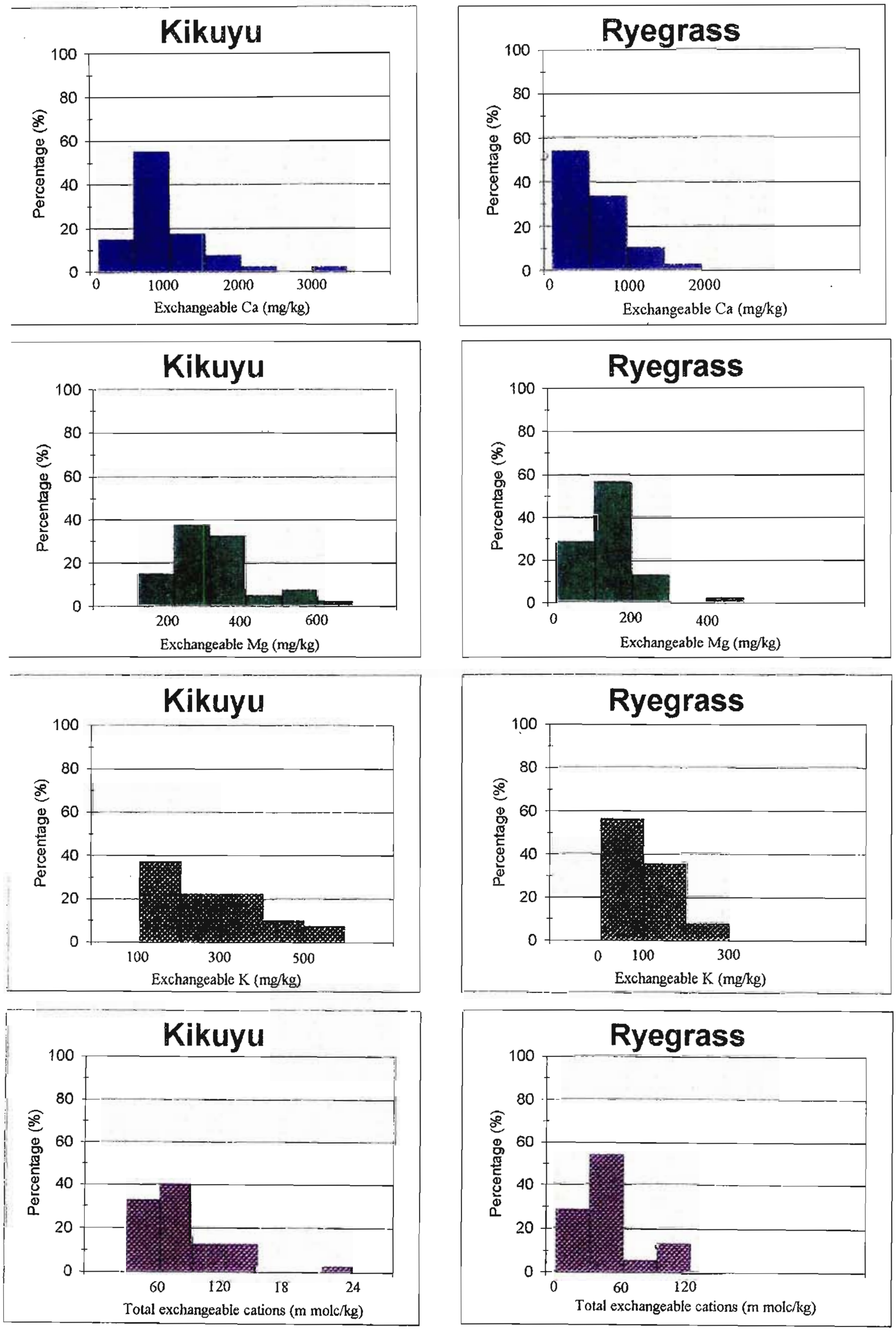
Region 3	Kikuyu				Annual			
Soil Nutrient	Mean	Std Error	Min	Max	Mean	Std Error	Min	Max
Organic C (g/kg)	65.323	3.120	54.255	81.818	46.486	5.131	26.050	70.330
pH$_{(water)}$	5.261	0.188	4.440	6.490	5.125	0.088	4.790	5.550
Exchangeable acidity (mmol$_c$ kg^{-1})	1.12	0.28	0.30	3.52	0.75	0.13	0.42	1.65
Extractable P (mg/kg)	88.007	19.194	6.122	184.444	73.550	15.877	25.743	158.000
Exchangeable Ca (mg/kg)	1,500.099	239.719	620.455	3,248.052	1,064.147	128.491	622.689	1,792.473
Exchangeable Mg (mg/kg)	346.243	33.240	211.702	549.351	223.465	34.908	120.168	445.745
Exchangeable K (mg/kg)	354.486	47.186	117.731	560.000	137.046	25.673	42.017	289.377
Total exchangeable cations (mmol$_c$ kg^{-1})	118.07	14.16	64.77	220.39	77.50	8.60	46.47	116.24
Extractable Zn (mg/kg)	25.290	7.160	2.160	71.169	9.435	2.635	3.663	28.800
Extractable Mn (mg/kg)	4.119	1.284	1.087	15.054	4.183	0.663	2.151	7.692
	no. = 10				no. = 9			



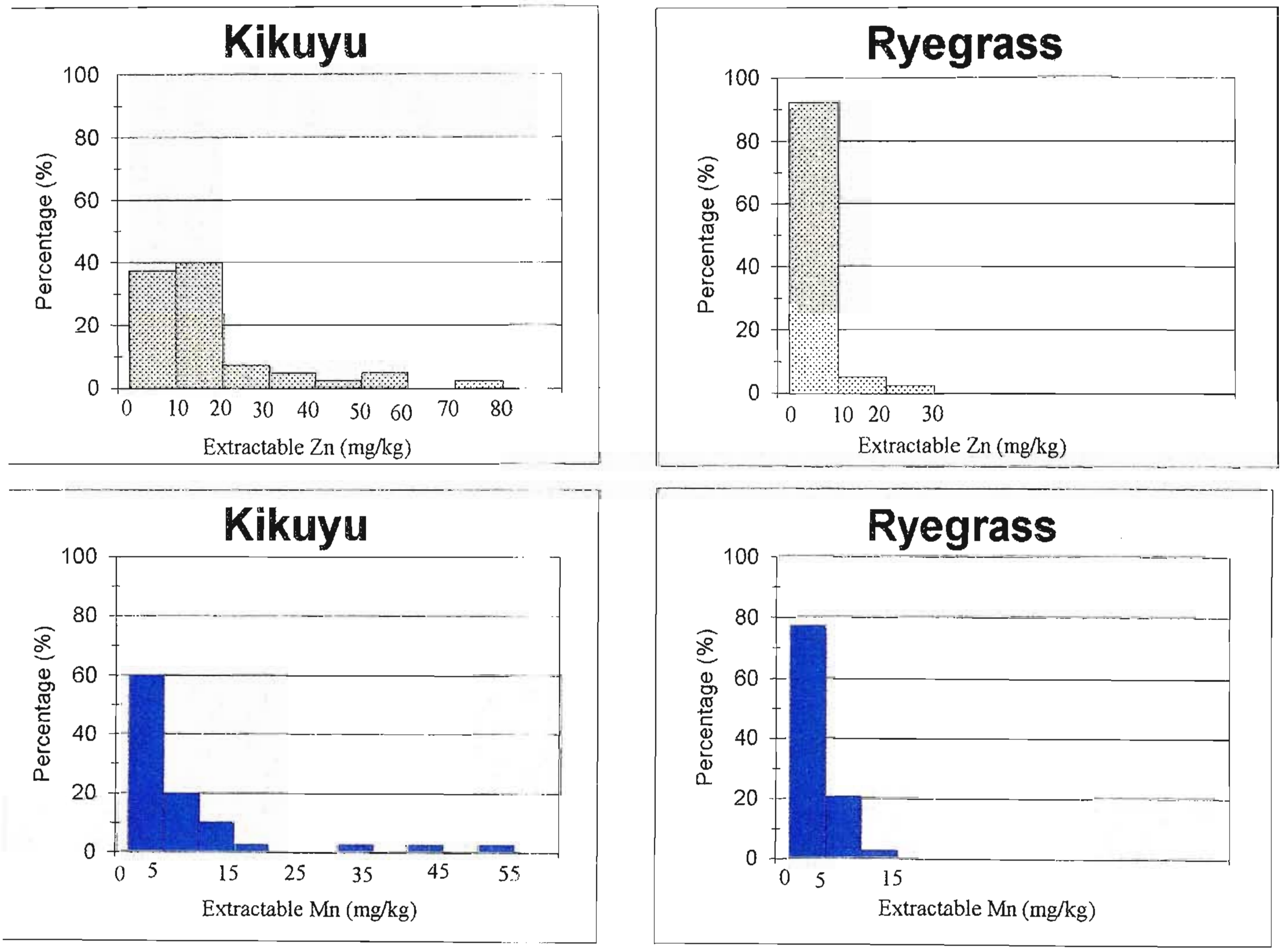
gure 5.1 Frequency distribution (%) of organic C, pH, exchangeable acidity and extractable P lues in soils under kikuyu and ryegrass pastures in the Tsitsikamma region.



igure 5.2 Concentrations of extractable P in the soil profile of two fields taken from each of the ree regions of the Tsitsikamma.



gure 5.3 Frequency distribution (%) of exchangeable Ca, Mg, K and total exchangeable cation ılues in soils under kikuyu and ryegrass pastures in the Tsitsikamma region.



gure 5.4 Frequency distribution (%) of extractable Zn and Mn values in soils under kikuyu and egrass pastures in the Tsitsikamma region.

5.3.2 Herbage properties

There were no clear differences in herbage nutrient contents between the three regions (Table 5.2). In general, in kikuyu herbage concentrations of tissue P and Cu were higher and those for Ca and Na lower than in ryegrass herbage.

The frequency distribution of herbage nutrient concentrations for data pooled from the three regions is presented in Figures 5.5, 5.6, 5.7 and 5.8. As noted above, in general the Ca concentration was lower for kikuyu than ryegrass herbage (Figure 5.5). The critical leaf Ca concentration is considered to be 0.11 and 0.25 % for kikuyu and ryegrass respectively (Miles, 1998). Thus, tissue Ca concentrations are adequate for pasture growth since less than 2 % and 1 % are below the required level for kikuyu and ryegrass respectively. If, however, the animal nutritional requirement of 0.43 - 0.66 % (National Research Council, 1988; Miles *et al.*, 1995), is considered, then much of the pasture herbage is deficient in Ca. That is, 55 % of the kikuyu and 41 % of the ryegrass fields had herbage Ca concentrations of below 0.4 %.

Phosphorus concentrations (Figure 5.5) were higher for kikuyu than ryegrass herbage and this is illustrated by the fact that only 33 % of the ryegrass samples were above 0.4 %, whilst 53 % of the kikuyu samples were above that concentration. The critical P content of grass herbage is 0.22 - 0.24 % (Miles, 1998), so few fields had low tissue P concentrations. The dietary P requirements for lactating dairy cows is generally reported to be between 0.28 and 0.41 % (National Research Council, 1988; Miles *et al.*, 1995). Most of the herbage P concentrations in both kikuyu and ryegrass samples were above 0.28 % and P supply to grazing livestock should, therefore, in most cases be adequate.

The critical K concentration in pasture herbage is approximately 2.0 - 2.2 % (Miles, 1998). Most of the herbage samples for both kikuyu (89 %) and ryegrass (82 %) were above 2.0 % (Figure 5.5) and K was not generally a limiting nutrient for pasture production. In terms of animal nutritional requirements, the K concentration required is only 0.5 - 0.8 % (Grunes and Welch, 1989), so concentrations in the herbage were well in excess of animal requirements. Excess K (i.e. above 3 %; Miles *et al.*, 1995) can, however, be problematic due to its effect on the absorption of other minerals particularly Ca and Mg. Kikuyu herbage generally had a higher K content than ryegrass with 60 % of kikuyu but only 30 % of ryegrass samples having concentrations above 3 %.

Table 5.2 Mean herbage nutrient content, standard error and range of values for kikuyu and ryegrass pasture in the three regions of the Tsisikamma.

Region 1	Kikuyu				Annual			
Plant Nutrient	Mean	Std Error	Min	Max	Mean	Std Error	Min	Max
Calcium (%)	0.386	0.023	0.270	0.570	0.426	0.032	0.260	0.660
Phosphorus (%)	0.369	0.033	0.200	0.580	0.386	0.025	0.260	0.560
Potassium (%)	2.741	0.255	0.720	4.160	2.691	0.195	1.760	4.470
Magnesium (%)	0.329	0.018	0.220	0.520	0.314	0.018	0.240	0.480
Sodium (%)	0.400	0.059	0.200	1.080	0.630	0.050	0.420	1.140
Nitrogen (%)	3.014	0.208	1.850	4.150	3.349	0.139	1.890	3.950
Sulphur (%)	0.273	0.022	0.160	0.480	.3.7	0.015	0.250	0.430
Zinc (mg/kg)	55.071	6.207	22.000	107.000	70.071	8.274	34.000	142.000
Manganese (mg/kg)	58.500	4.273	39.000	89.000	80.429	5.865	37.000	122.000
Copper (mg/kg)	6.214	0.909	2.000	13.000	3.929	0.588	0.000	9.000
Boron (mg/kg)	12.571	0.830	6.000	18.000	13.357	1.036	6.000	20.000
	no. = 15				no. = 14			

Region 2	Kikuyu				Annual			
Plant Nutrient	Mean	Std Error	Min	Max	Mean	Std Error	Min	Max
Calcium (%)	0.391	0.033	0.100	0.720	0.425	0.031	0.260	0.590
Phosphorus (%)	0.453	0.032	0.100	0.630	0.375	0.034	0.220	0.570
Potassium (%)	3.358	0.239	0.940	4.670	2.811	0.339	0.930	5.150
Magnesium (%)	0.317	0.021	0.100	0.440	0.292	0.012	0.250	0.350
Sodium (%)	0.295	0.024	0.120	0.470	0.415	0.052	0.120	0.600
Nitrogen (%)	3.465	0.115	2.520	4.100	2.967	0.218	1.360	4.090
Sulphur (%)	0.329	0.015	0.220	0.410	0.304	0.022	0.160	0.400
Zinc (mg/kg)	66.467	6.878	14.000	120.000	59.364	5.672	25.000	89.000
Manganese (mg/kg)	81.800	7.920	16.000	140.000	90.818	7.908	31.000	134.000
Copper (mg/kg)	7.533	0.584	2.000	11.000	6.545	0.813	2.000	11.000
Boron (mg/kg)	8.067	0.733	2.000	14.000	7.273	0.449	6.000	9.000
	no. = 15				no. = 11			

Region 3	Kikuyu				Annual			
Plant Nutrient	Mean	Std Error	Min	Max	Mean	Std Error	Min	Max
Calcium (%)	0.389	0.026	0.270	0.500	0.453	0.034	0.310	0.610
Phosphorus (%)	0.456	0.031	0.350	0.660	0.413	0.015	0.360	0.480
Potassium (%)	2.942	0.379	1.690	5.000	2.954	0.265	1.640	4.230
Magnesium (%)	0.311	0.019	0.210	0.400	0.279	0.016	0.210	0.360
Sodium (%)	0.378	0.062	0.120	0.720	0.476	0.053	0.330	0.800
Nitrogen (%)	3.147	0.243	1.650	4.010	3.169	0.116	2.750	3.800
Sulphur (%)	0.034	0.031	0.240	0.520	0.349	0.020	0.280	0.460
Zinc (mg/kg)	47.444	2.977	36.000	61.000	44.000	1.427	39.000	49.000
Manganese (mg/kg)	48.444	7.509	23.000	95.000	70.375	13.608	36.000	135.000
Copper (mg/kg)	5.333	0.928	2.000	9.000	4.500	0.627	2.000	8.000
Boron (mg/kg)	7.556	0.709	4.000	11.000	7.625	0.498	6.000	9.000
	no. = 9				no. = 8			

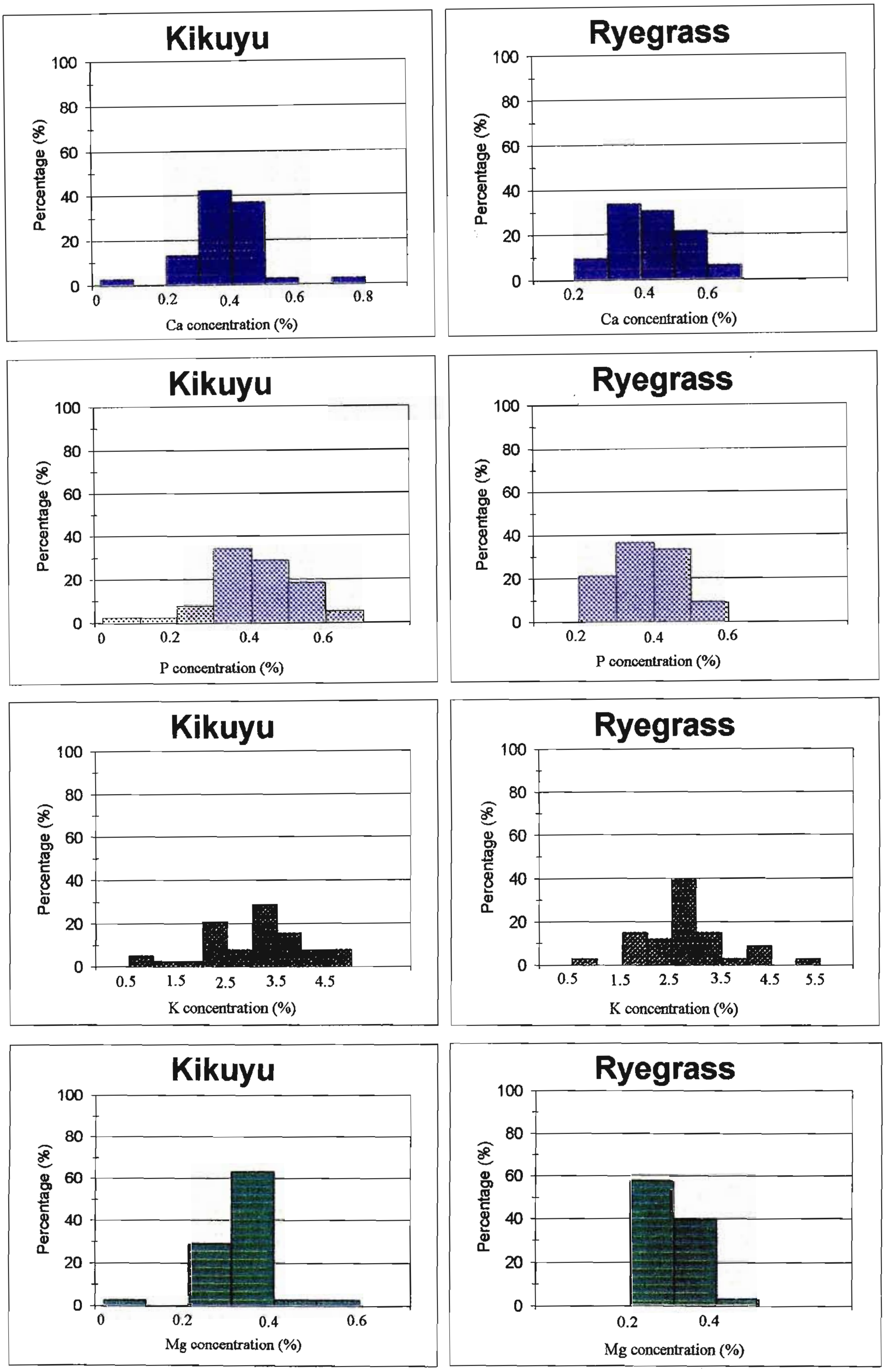


Figure 5.5 Frequency distribution (%) of Ca, P, K and Mg concentrations in herbage from kikuyu and ryegrass pastures in the Tsitsikamma region.

The Mg concentration in pasture herbage considered to be critical for growth is approximately 0.10 % (Miles, 1998). As can be seen from Figure 5.5 all the concentrations in ryegrass and 97 % in the kikuyu were above this level. A nutritional Mg requirement in forage for high producing dairy cows of 0.2 % is considered sufficient (Grunes and Welch, 1989) and again all the ryegrass and 97 % of the kikuyu herbage samples were above this level. High K levels can, however, have inhibitory effects on Mg absorption.

The Na concentrations (Figure 5.6) were considerably higher in ryegrass than kikuyu herbage, with only 26 % of kikuyu samples above 0.4 % whilst 78 % of the ryegrass samples were above that same concentration. The recommended concentration of Na in feed for grazing animals is approximately 0.12 % (Holmes and Wilson, 1987) and both kikuyu (90 %) and ryegrass (95 %) were well in excess of this requirement, accordingly no apparent Na problems should exist.

The critical N concentration for pasture growth is approximately 2.7 - 3.5 % (Miles, 1998) and the nutritional requirement for lactating dairy cows is between 1.9 and 3.0 % (Whitehead, 2000). Seventy percent of kikuyu and 73 % of ryegrass values were above 3.0 % (Figure 5.6), reflecting the heavy rates of fertilizer N used in the region. Most of the herbage samples had an S concentration of between 0.2 and 0.4 % (Figure 5.6). The critical concentration for pasture growth is approximately 0.12 - 0.20 % (Miles, 1998); the nutritional S requirement is very similar and about 0.16 - 0.2 % (Whitehead, 2000) Less than 8 % of the kikuyu and 3 % of the ryegrass were below 0.2 %, consequently there is little or no expected problem with the S concentrations for pasture growth or animal nutrition.

The Ca : P ratio in feed is considered important in terms of animal nutrition and results are shown in Figure 5.7. This ratio should ideally not be below 1:1 (Bredon, 1980), but 65 % of the kikuyu and 42 % of ryegrass samples were below this value. The K : Ca + Mg is another ratio that is important and is often used as an indicator of the potential for grass tetany (Holmes and Wilson, 1987). The ratio is recommended not to be above 2.2 (Miles *et al.*, 1995), but from the results (Figure 5.7) it can be seen that 30 % of the kikuyu and 21 % of the ryegrass samples had ratios above 2.0. The N : S ratio in herbage (Figure 5.7) was higher in the kikuyu herbage samples than in the ryegrass samples, with 61 % of the kikuyu herbage samples having values > 10, whilst only 50 % of the ryegrass herbage samples were > 10.

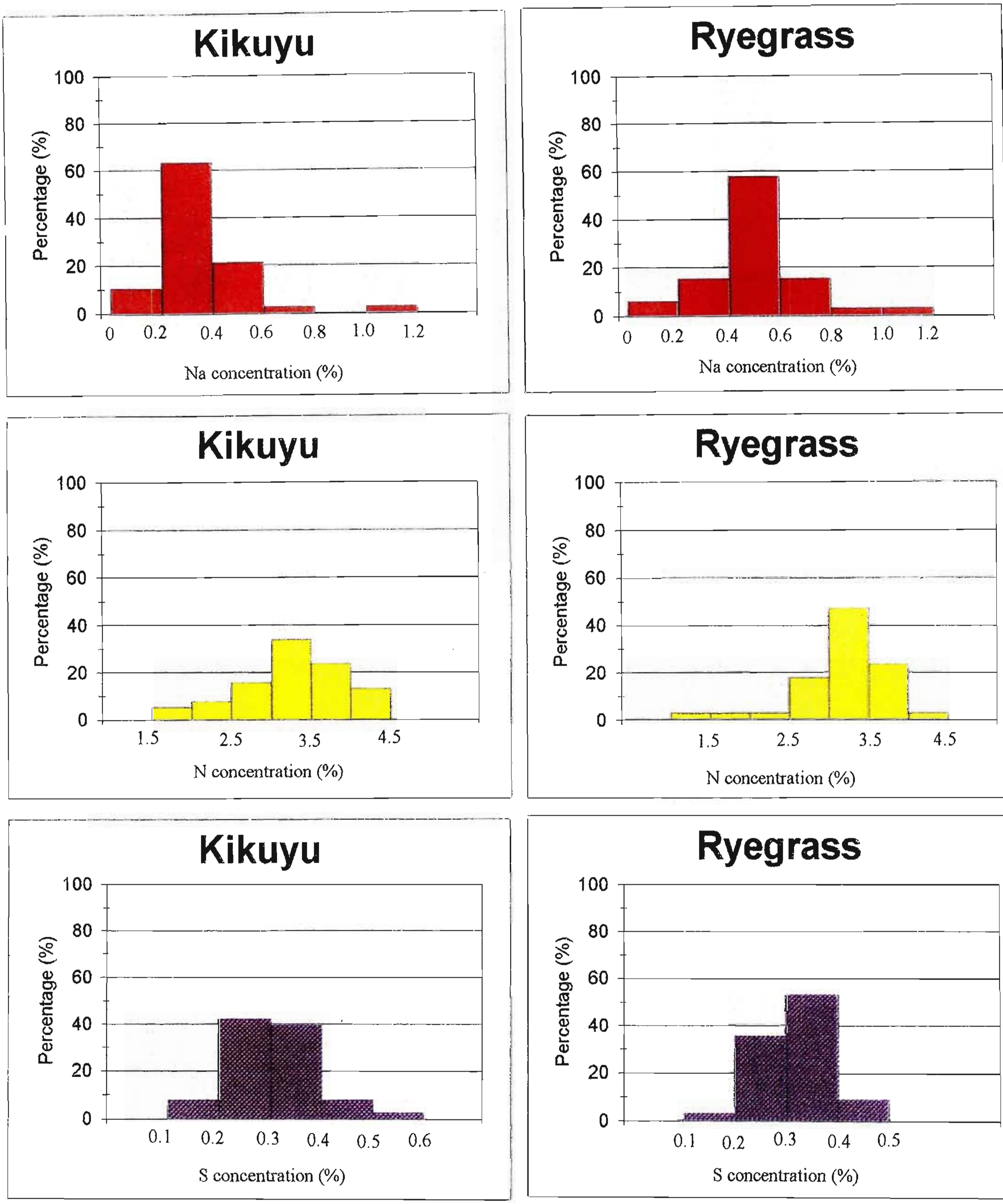
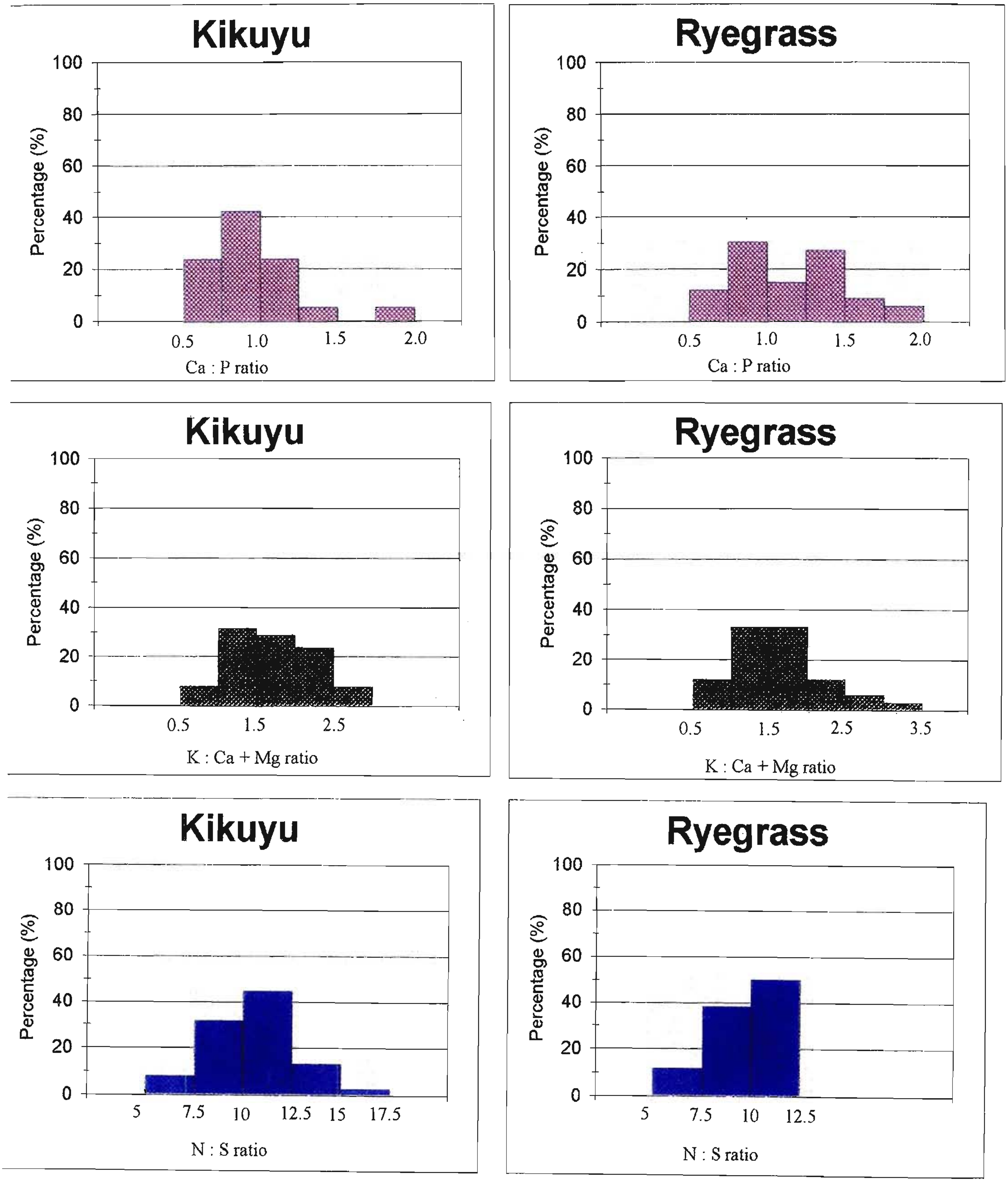
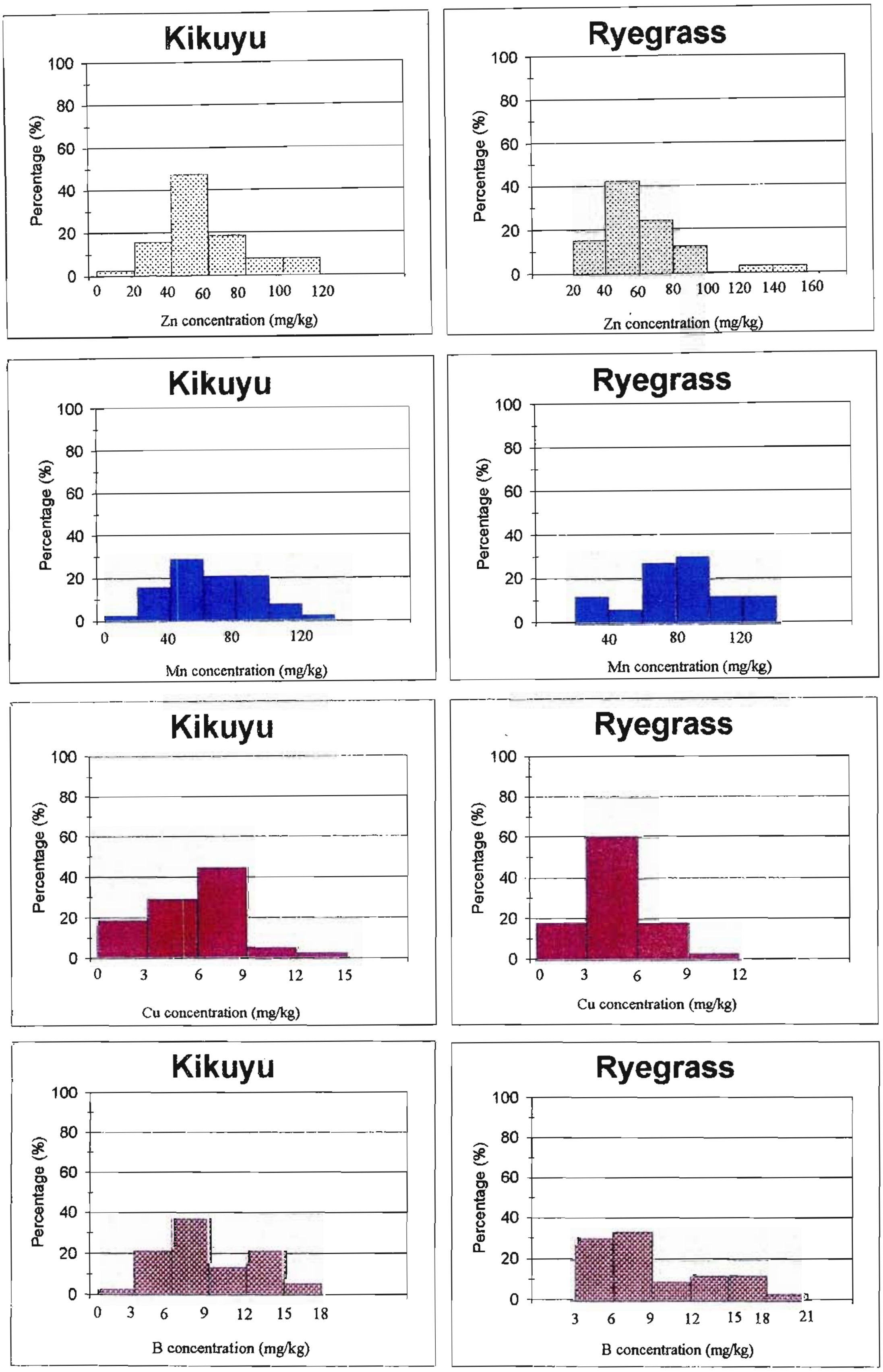


Figure 5.6 Frequency distribution (%) of Na, N and S concentrations in herbage from kikuyu and ryegrass pastures in the Tsitsikamma region.

The Zn, Mn, Cu and B content of herbage is presented in Figure 5.8. For herbage Zn content, the largest percentage of samples (47 % for kikuyu and 42 % for ryegrass) were in the 40 - 60 mg kg^{-1} range. The critical level of Zn for pasture growth is 10 - 13 mg kg^{-1} (Miles, 1998) and all the ryegrass and 97 % of the kikuyu samples were above 20 mg kg^{-1}. Thus, Zn supply is unlikely to be a factor limiting pasture production. The nutritional requirement for Zn for dairy cows is about 26 mg kg^{-1} (Miles and Tainton, 2000), and 97 and 100 % of the kikuyu and ryegrass samples respectively are above 20 mg kg^{-1}. The adequate range for Mn is approximately 50 - 60 mg kg^{-1} (Holmes and Wilson, 1987) and 55 % of the kikuyu and 82 % of the ryegrass were above 60 mg kg^{-1}. The nutritional requirement is, however, only about 25 mg kg^{-1} (Miles and Tainton, 2000) and 97 and 100 % of the kikuyu and ryegrass samples respectively are above 20 mg kg^{-1}. Copper concentrations were most frequent in the 3 - 6 mg kg^{-1} range for ryegrass, but in the 6 - 9 mg kg^{-1} range for kikuyu. Fifty four percent of kikuyu and 21 % of ryegrass samples were above 6 mg kg^{-1}, (the critical level for pasture growth is about 5 mg kg^{-1}; Miles, 1998), indicating that the supply of Cu in these soils is sub-optimal. Nutritionally, the dietary requirement for Cu is approximately 10 mg kg^{-1} (Whitehead, 2000), and only 8 and 3 % of the kikuyu and ryegrass samples respectively were above 9 mg kg^{-1}, indicating a need for Cu supplementation. The adequate range for pasture for B is approximately 5 -15 mg kg^{-1} (Miles, 1998) and 77 and 70 % of the kikuyu and ryegrass samples respectively were above 6 mg kg^{-1}.



gure 5.7 Frequency distribution (%) of nutrient ratios in herbage from kikuyu and ryegrass stures in the Tsitsikamma region.



gure 5.8 Frequency distribution (%) of Zn, Mn, Cu and B concentrations in herbage from kuyu and ryegrass pastures in the Tsitsikamma region.

5.4 Discussion

5.4.1 Soil properties

As expected organic C content (Figure 5.1) under kikuyu was much higher (approximately double) than that under annual ryegrass pastures. This highlights both the negative effect of annual cultivation (often using a rotary cultivator) and the positive effect of permanent pasture on the soil organic matter content. As discussed in chapter three, soil organic matter plays a central role in determining the chemical, biological and physical properties of the soil and a loss of soil organic matter often leads to a loss of soil quality (Gregorich *et al.*, 1994; Karlen and Cambardella, 1996). The breaking and mixing of soil clods during cultivation introduces more oxygen into the soil which increases both the activity of the aerobic microorganisms (Cannell and Hawes, 1994) and the surface area of the organic matter exposed for microbial attack. This in turn leads to a flush of microbial activity and the degradation of organic matter. Thus, annually cultivated soils generally have a much lower organic matter content than those that are not subject to cultivation (Haynes and Beare, 1996). The positive effects of permanent pasture are mainly related to the very large inputs of organic matter (particularly via root turnover) (Haynes and Beare, 1996) that typically occur under permanent grazed pastures.

Since the recommended liming rates are generally similar for kikuyu and ryegrass pastures (e.g. about 2 Mg ha^{-1}) the lower pH under ryegrass suggests a greater rate of soil acidification than that under kikuyu pasture. Two important factors may have contributed to greater acidification under annual pastures. Firstly, during the degradation of organic matter, induced by annual cultivation, soil organic N will have been mineralised and nitrified. Nitrification is an acidifying process and one H^+ ion is produced per mole of NH_4^+ converted to NO_3^- (He *et al.*, 1999). Secondly the loss of organic matter will have resulted in a lower cation exchange capacity and less buffering capacity (Blevins and Frye, 1993). Applications of NH_4^+-containing or forming fertilizers (e.g. urea) to both types of pasture will be acidifying (upon nitrification), but acidification will be more pronounced under the annual pastures because of the lower buffering capacity. Nitrogen application rates to both types of pasture in the region are commonly in the range of 200 - 300 kg N ha^{-1} yr^{-1}. If the nitrate produced by nitrification is lost from the system (e.g. leached) then acidification is permanent (He *et al.*, 1999). Nitrate is usually leached from soils with Ca^{2+}, Mg^{2+} and to a lesser extent K^+, as counterions (He *et al.*, 1999). Thus, the generally lower soil pH values under ryegrass than kikuyu were accompanied by lower concentrations of exchangeable Ca, Mg and K and a tendency for higher values for exchangeable acidity. Exchangeable acidity represents the directly exchangeable Al^{3+} (plus H^{+}) in the soil (Rowell, 1988) and as the pH declines soil Al becomes solubilized.

The extractable P results (Figure 5.1) indicate that the P fertility status of dairy pasture soils is high. This is particularly so under kikuyu pastures where 55 % of samples showed values above 80 mg P kg^{-1}. These values are due to the high rates of fertilizer P that have been historically applied. For example, annual application rates have been transferred from other dairy farming areas of the world such as the central North Island of New Zealand, where high P-fixing volcanic soils predominate. However, the P sorption capacity of the sandy soils of the Tsitsikamma is generally low and recommended maintenance P rates are usually about 25 kg P ha^{-1} (N. Miles, personal communication 2001). Rates greater than 50 kg P ha^{-1} yr^{-1} are routinely applied on some farms and as a result soil test P values are very high.

In addition, as demonstrated in Figure 5.2, high levels of extractable P occur at well below the 0 -10 cm layer. For example, at sites 2, 3 and 5 concentrations were at or above 50 mg P kg^{-1} to a depth of 40 cm and they were above 16 mg P kg^{-1} to 80 cm at sites 2 and 3 and to 60 cm at site 5. Some of this downward movement of P may have occurred due to the pasture being turned over at some time (e.g. field 5) but much of the downward movement in regions 1 and 2 may have occurred due to the low P sorption capacity of these sandy soils. The high application rates may have effectively saturated P adsorption sites in the surface soil thus allowing substantial downward movement of P by leaching. The magnitude of the P reserves now present in many of these soils is somewhat excessive and in many cases maintenance fertilizer P rates could be reduced substantially and in some cases even withdrawn (in the short term) without any detrimental effects on pasture production. Adequate P at planting (seed or vegetative material) has been shown to promote rapid pasture establishment, and thus earlier utilization and also to minimize the effects of weed competition (Barber, 1980). Thus, adequate P fertilization is essential, particularly for annual pastures, but excessive applications will be economically unsustainable.

As already noted exchangeable Ca, Mg and K (Figure 5.3) were all higher under kikuyu than annual pastures. For ryegrass pastures, 28 % of exchangeable Mg and 56 % of exchangeable K values were below 100 mg kg^{-1} and 53 % of exchangeable Ca concentrations were below 500 mg kg^{-1}. Such low soil test values suggest that additional fertilizer dressings should be applied in these cases. The low values are of concern as Ca is important in the growth of meristems, especially in the development and functioning of root tips and is required by a number of enzymes (Clarkson and Hanson, 1980; Blevins, 1994; Whitehead, 2000). Calcium is therefore vitally important and the amount of exchangeable Ca directly effects pasture growth and in turn ruminant health and production. The fact that the K concentrations were also occasionally inadequate under ryegrass is problematic as K is vital for the maintenance of osmotic potential and as a result, plants that are deficient in K are more susceptible to drought (Whitehead, 2000). Potassium is also an activator of a large number of enzymes, including some involved in protein synthesis (Blevins, 1994; Whithead, 2000) and is hence important for optimum pasture growth. Under kikuyu pastures, the very high levels of exchangeable Mg (85 % were above 200 mg kg^{-1}) and exchangeable K (62 % were above 200 mg kg^{-1}) presumably reflect large fertilizer applications of these nutrients to pastures. The high levels of exchangeable Mg are desirable from an animal health viewpoint (if they are translated into high tissue Mg concentrations) (Miller, 1979; Whitehead, 2000). However, the high exchangeable K values are less desirable since, through cationic competition, they may result in a reduction in uptake of Mg and Ca in grass herbage (McNaught, 1959; Mudd, 1970; Lightner *et al.*, 1983; Whitehead, 2000).

The soil micronutrient cations, Zn and Mn (Figure 5.4) also followed the above trend with higher concentrations and a greater range under kikuyu than ryegrass. Although only small amounts of micronutrient cations are added to soils through their presence as incidental constituents of fertilizers, Zn occasionally occurs in large amounts in phosphate fertilizers (Dam Kofoed, 1980; Whitehead, 2000). This conforms with the above results as both the Zn and P concentrations are more than adequate under both kikuyu and ryegrass, possibly suggesting a high Zn content in the applied phosphate fertilizer. The Mn concentrations, on the other hand, were considered adequate and in excess of the dietary requirement of ruminants. Although micronutrients are required in much smaller amounts they still perform vitally important functions in the soil, plants and animals and adequate quantities are recommended for optimum growth and health.

5.4.2 Herbage analysis

Herbage analysis results are important because they provide a mechanism of quantification that allows calculation of the amount of pasture (and supplements) required for a specified level of animal performance (Holmes and Wilson, 1987). There is mounting evidence that gross mineral imbalances in forages may seriously be impacting on animal performances and health (Brendon, 1980). This is especially the case in dairy cows as they are susceptible to mineral imbalances due to the high demands of pregnancy and lactation and even marginal mineral deficiencies can reduce growth, reproduction and health in ruminants (Holmes and Wilson, 1987). Thus, reliable nutrient analysis of herbage is an essential tool for dairy farm management.

Although the Ca concentrations in foliage (Figure 5.5) were lower for kikuyu than ryegrass, this was expected since herbage Ca concentrations are characteristically low in kikuyu grass (Marais, 1990). Nevertheless, both kikuyu (0.11 %) and ryegrass (0.25 %) had adequate Ca contents for optimum pasture growth (Miles, 1998). The dietary requirements for dairy cows are, however, different and for the cations, Ca, K, Mg and Na they are substantial mainly due to the needs of lactation (Whitehead, 2000).

Concern regarding the supply of Ca to animals grazing kikuyu has been shown by many researchers (Marais, 1990) and if the nutritional Ca requirement is considered (0.43 - 0.66 %) (National Research Council, 1988; Miles *et al.*, 1995) it is apparent that there is frequently a deficiency and feed supplementation is necessary. Calcium is the second most abundant nutrient element (after N) in the animal body, and in milk, and it performs many important enzyme-related functions (Whitehead, 2000). Deficiencies have been found to impair the reproductive performances in a number of herds (Miles *et al.*, 1995). Other deficiencies symptoms include; reductions in the overall growth and development of animals (National Research Council, Subcommittee, 1989; Whitehead, 2000), bone fractures (Naylor, 1991; Whitehead, 2000), reductions in milk production and severe deficiencies can cause the onset of milk fever (Whitehead, 2000). The risk of deficiency is increased by high rates of N and K fertilizers (Cornforth, 1984), and it is further aggravated by the fact that the bulk of a kikuyu pasture's production is in the midsummer months when Ca levels are typically at their lowest. In addition much of the Ca in kikuyu forms insoluble complexes with oxalate which renders it largely unavailable for absorption by animals (Reason *et al.*, 1989; Marais, 1990). It follows that the total herbage Ca concentrations, particularly in kikuyu, are an exaggeration of the amount available to animals and alternate supplies of Ca, whether from supplementation or the inclusion of a Ca-accumulating legume are necessary.

The herbage P concentrations (Figure 5.5) followed the expected trend of having a higher concentration and a greater range under kikuyu pastures. This was expected since the P content of kikuyu herbage has often been shown to be higher than that encountered in other grass species, for example ryegrass (Miles *et al.*, 1995). In terms of pasture growth and production, the majority of the fields, under both kikuyu and ryegrass, were above the necessary requirement (0.22 - 0.24 %) (Miles, 1998). This is important because P is intimately involved in the transfer of energy through ADP and ATP, as well as other essential processes such as cell division within the plant (Whitehead, 2000). The generally high herbage P results can be explained by the high extractable P levels found in most of the soils (Figure 5.1). In turn, the dietary P requirement (0.28 - 0.41 %) (National Research Council, 1988; Miles *et al.*, 1995), was also predominately satisfied under both kikuyu and ryegrass. An adequate P supply is important because of the essential functions that P performs in the animal, such as its role as a structural component in the skeleton and teeth (National Research Council, Subcommittee, 1989; Whitehead, 2000), in the transfer of energy and its role in various other essential processes (Underwood and Suttle, 1999).

Excessive applications of P often cause a decrease in the total uptake of Zn and sometimes Cu by plants (Stukenholtz *et al.*, 1966; Haynes, 1984). In this study no significant correlations were found between soil P and leaf Zn and Cu concentrations but a highly significant negative correlation between leaf P and leaf Zn was recorded ($r = -0.60$***; $P \leq 0.001$) for kikuyu grass. The corresponding correlation was not, however, significant for ryegrass. This is presumably related to the considerably higher concentrations of extractable soil P recorded under kikuyu than ryegrass. Various mechanisms by which P inhibits Zn uptake have been identified and include, enhancement of Zn adsorption by variable charge surfaces in the soil following phosphate adsorption, resulting in decreased absorption of Zn by plant roots (Stanton and Burger, 1967; Marinho and Igue, 1972; Saeed and Fox, 1979; Haynes, 1984) and antagonism between phosphate and Zn in the uptake and translocation processes in plants (Stukenholtz *et al.*, 1966; 1974; Safaya, 1976; Haynes, 1984).

The evaluation of various nutrient ratios in forage has been identified as important in terms of animal nutrition. The tendency for there to be an interaction between Ca and P in terms of their absorption by animals (Little, 1982; Miles *et al.*, 1995) has resulted in considerable emphasis being placed on the Ca to P ratio in feeds and forages. A dietary Ca : P ratio of between 1:1 and 2:1 is often considered to be ideal for growth and bone formation, (since this is the approximate ratio in bone) (Whitehead, 2000) and it has been recommended by many animal nutritionists that the ratio should not go below 1:1 (Miles *et al.*, 1995). It is important to note that a substantial portion of the herbage samples (65 % for kikuyu and 42 % for ryegrass) had ratios below 1 : 1 (Figure 5.6). Kikuyu invariably contains more P than Ca (Miles *et al.*, 1995), (i.e. it tends to accumulate phosphorus thus reducing the Ca : P ratio). This accounts for the larger percentage of kikuyu than ryegrass samples being below the recommended value. This, again, emphasises the low Ca content of the herbage samples. The substantial portion of samples, particularly for kikuyu, that had values in the range of 0.5 to 0.75 : 1 is concerning since there are numerous difficulties involved in correcting the rations of dairy cows with forage ratios as low as 0.5 : 1. For example, it is difficult to correct such an imbalance with feedlime without creating other metabolic disturbances (Brendon, 1980).

Both K and Mg are important nutrients and perform several vital functions in plants and animals. Potassium is involved in the maintenance of the optimum amount of water in tissues, as well as the activation of several enzymes involved in protein synthesis (Ammermann and Goodrich, 1983), while Mg is a component of bone and is involved in membrane functioning (Naylor, 1991; Underwood and Suttle, 1999) and energy metabolism (Underwood and Suttle, 1999). Most of the K and Mg concentrations in both kikuyu and ryegrass herbage (Figure 5.5) were above critical values for both pasture growth and dietary requirements of cows. Excess K is, however, a concern as the majority of pasture species take up K far in excess of plant requirements and this phenomenon is known as "luxury uptake". This luxury uptake has negative effects and is associated with marked decreases in plant concentrations of Ca, Mg and Na (Miles, 1991), which in turn reduces the dietary availability of these cations. In this study, no negative correlation was found between herbage K and herbage Ca + Mg for ryegrass but for kikuyu the relationship was significant ($r = -0.47^{**}$; $P \leq 0.01$). This suggests that the high K uptake by kikuyu was tending to decrease Ca and Mg accumulation.

Although the excess K taken in by animals is rapidly excreted, mainly through the urine, high levels of K can impact negatively on animal health and productivity (Castle and Watkins, 1984) especially through it's inhibitory effect on Mg absorption by animals (Little, 1982; Miles *et al.*, 1995). These cation imbalances, have been implicated in the incidence of a number of animal health problems such as, hypomagnesaemia (grass tetany) (Reid and Jung 1974; Miles, 1991) hypocalcaemia (milk fever) (Beede, 1992; Miles *et al.*, 1995), infertility (Dugmore *et al.*, 1987), bloat (Reason *et al.*, 1989; Miles, 1991) and a reduction in milk yields (Holmes and Wilson, 1987). A maximum tolerable K concentration of 3.0 % in the diet of dairy cows has been suggested by the National Research Council (National Research Council, 1988; Miles *et al.*, 1995). About 58 % of kikuyu samples and 30 % of ryegrass samples had values above 3 %. Accordingly, an important goal in the management of pastures, particularly kikuyu, should be the reduction of herbage K levels.

There is often a positive correlation between N and K uptake in pasture herbage because increased NO_3^- uptake by plants is typically accompanied by greater cation (especially K) uptake (Marschner, 1995). In this study, the correlation between herbage N and K content was not significant for ryegrass but for kikuyu it was highly significant (r = 0.59***; P≤0.001). In order to limit K accumulation in kikuyu pasture herbage, it is important to manage N applications judiciously (Miles and Tainton, 2000). Frequent small dressings of N are preferable to infrequent heavy dressings.

These cation imbalances, that typically occur in the diet of ruminants, for example a Mg deficiency, has given rise to the evaluation of the cation K : Ca + Mg (Figure 5.7), which is often used as an indicator of the potential for hypomagnesaemia (grass tetany). Although hypomagnesaemia *per se* is due to inadequate Mg, the symptoms may well be accentuated by a low concentration of Ca (Whitehead, 2000), which is also more prevalent in cases of high K levels in the ruminant diet. Values greater than 2.2 have been associated with an increased incidence of tetany in grazing animals (Grunes and Welch, 1989). About 28 % of kikuyu herbage samples and 18 % of ryegrass samples exceeded this value (Figure 5.7). It is also worth noting that rates as high as 3.3 were recorded. For kikuyu it has already been noted that Ca absorption by cows is severely restricted by the presence of oxalates and this in turn indicates the possible underestimation of the value of the ratio for tetany index for kikuyu pastures. In light of this, supplements of both Ca and Mg are undoubtably required to prevent any ill effects in terms of animal health or production.

Sodium is another essential cation that is intimately involved in bodily functions such as the maintenance of osmotic pressure and pH and the transport of amino acids and glucose (Ammermann and Goodrich, 1983). It is notable that Na concentrations in kikuyu tissues were generally lower than those in ryegrass (Figure 5.6). This was, however, expected as ryegrass is a known natrophile, which accumulates large amounts of Na in their leaves, whilst kikuyu is a natrophobe and not expected to accumulate Na to any extent (Fulkerson *et al.*, 1998; Miles and Tainton, 2000). The concentrations under both kikuyu and ryegrass are, however, far in excess of the dietary requirement of 0.12 % (Holmes and Wilson, 1987). It is possible that a significant portion of the measured Na was in fact deposited on the leaf surfaces, (due to the proximity of the ocean and inputs in the form of Na chloride from the sea spray) rather than inside the leaf tissue. It is worth noting that lactating dairy cows are particularly susceptible to Na deficiency due to the large amounts of Na secreted in milk (Holmes and Wilson, 1987) and if these cows are pastured on kikuyu outside of a coastal vicinity it is vitally important that Na supplements are supplied.

Nitrogen is required by plants in larger amounts than any other nutrient element and it performs many essential functions within both plants and animals. For example, it is an essential component of proteins, vitamins and hormones (Whitehead, 2000). The N concentrations (Figure 5.6) under both kikuyu and ryegrass follow very similar profiles and are generally not limiting to either pasture growth or in terms of nutritional requirement. The nutritional requirement is, however, greatly influenced by the physiological state of the animal, being highest in lactating and young animals and ranges from about 1.9 - 3.0 % (National Research Council, Sub Committee, 1989; Whitehead, 2000). Sulphur, like N, is an essential constituent of plant proteins and it is also essential for the synthesis of microbial biomass in the rumen. It therefore, serves a vital role in digestion (Holmes and Wilson, 1987). Again, like N, S concentrations (Figure 5.6) had similar profiles under both kikuyu and ryegrass and were in excess of both the pasture and nutritional requirements.

In ruminants, the nutritional requirements for S are closely related to those for N, since both elements are assimilated into microbial protein in the rumen and into the protein of body tissues (Whitehead, 2000). Since both nutrients were generally in excess there should be no nutritional problems. While some farmers and consultants in the area suspect S deficiencies, the proximity of the area to the sea means that inputs of S in the rainfall (Paul and Clark, 1996) are likely to ensure an adequate supply of S. Various other factors, such as fertilizer applications can also influence the concentration of nutrients and of particular concern to S is the application of N fertilizer which tends to reduce the concentrations of S in herbage if supplies of S are limiting (Goh and Kee, 1978; Whitehead, 2000), but increase the concentration if S supplies are plentiful (Salette, 1978; Whitehead, 2000). The N : S ratio (Figure 5.7) was higher in the kikuyu herbage mainly due to higher N fertilizer application rates under kikuyu than ryegrass pastures.

The concentrations of Zn, Mn, Cu and B in herbage (Figure 5.8) were generally higher under kikuyu than ryegrass. These micronutrients perform vital functions within plants which are generally related to the changing of their oxidation state and /or their ability to form complexes with organic molecules (Mengel and Kirkby, 1987; Whitehead, 2000), while in animals they mainly function as constituents of enzymes or as enzyme activators (Whitehead, 2000). The Zn, Mn and B concentrations were generally in excess of the pasture and nutritional requirements and therefore pose no obvious problems. Copper was, however, generally lacking in relation to animal nutrition and in many cases, also in relation to plant nutrition. In the latter cases, fertilizer Cu should be applied. Copper deficiency is known to cause poor animal growth, loss of hair pigmentation as well as the increase of the susceptibility of animals to disease (Underwood and Suttle, 1999). Adequate supplementation will therefore be necessary to avoid such problems.

5.5 Conclusions

It is clear that a substantial loss of soil organic matter has occurred under annual ryegrass compared with the kikuyu pastures. Along with the decreased organic matter content, there was increased soil acidification and a loss of exchangeable cations. From the large concentrations of extractable P and exchangeable K measured in soils it was concluded that the rates of applied P, and sometimes K, tended to be excessive (particularly under kikuyu) and in many cases these could be reduced.

Herbage analyses highlighted various nutritional concerns. These included the need for Ca supplementation, particularly under kikuyu, due to the low herbage Ca concentrations. The low Ca : P ratio measured in ryegrass, and more particularly in kikuyu herbage, highlighted the low Ca content of herbage and also the tendency of kikuyu grass to accumulate large concentrations of P. The large K concentrations and high K : Ca + Mg ratios recorded in a significant number of herbage samples suggests the potential for animal nutritional problems such as hypomagnesaemia. The excessive K and generally low herbage Ca concentrations encountered are potentially problematic and an important goal of pasture management strategies in the region should therefore be to reduce the soil K levels, particularly under kikuyu.

The other macronutrient requirements, both for pasture and diet have generally been satisfied and pose no obvious problems. The micronutrient concentrations of Zn, Mn and B were generally adequate for pasture and dietary requirements and were higher under kikuyu than ryegrass. Copper was, however, potentially limiting and fertilizer applications and/or feed supplementation is therefore required.

Although kikuyu is an excellent pasture in terms of dry matter production it tends to be deficient in Ca (and sometimes Na) and can contain prohibitively high K levels, which are likely to induce Mg deficiencies in grazing animals. Feed supplements containing Ca, Mg and Na are recommended particularly where kikuyu is the main feed ration. Given such supplementation, then kikuyu is definitely a very viable option as a pasture in the Tsitsikamma region.

CHAPTER 6

GENERAL CONCLUSIONS

A dairy farming system is very complex, (involving soil-plant-animal interactions) and a holistic approach is required to obtain a full understanding of such an agricultural system. The central role of organic matter in soil quality has been highlighted throughout this study and soil type as well as many facets of management have impacted on the amount of C present in the soil. This, in turn, has impacted on soil physical, chemical and biological properties. Accordingly, the choice of management practice is vitally important and the use of a combination of chemical, physical and biological indicators of soil quality is necessary to evaluate practices. The complexity of pastoral systems, and the fact that soil quality is site and function specific, and therefore dependent on climatic, soil, topographic, economic and social conditions, means that soil properties also need to be considered in relation to the system being used and the study locality. Certainly, land owners and managers should strive to prevent the loss of organic C and the associated degradation of the soil resource, especially beyond a critical level where the soil's ability to recover or restore itself is either lost or severely disrupted and soil quality becomes a limiting factor to pastoral production.

Typically, there is an increase in organic matter content under permanent kikuyu pastures and a decrease under annually cultivated ryegrass pastures. The effect of locality, was, however very pronounced with an increase in organic matter (relative to the native vegetation) occurring under both annually cultivated ryegrass and permanent kikuyu pastures on the very sandy low rainfall, eastern end of the Tsitsikamma. By contrast, at the higher rainfall western end there was a loss of soil organic matter under both types of pasture. Despite this, soil organic C content was lower under annual ryegrass than permanent kikuyu pasture at all the sites reflecting the degrading effect of annual cultivation on soil organic matter. By contrast, the positive effect of a permanent grazed pasture on soil microbial activity was demonstrated by grazed kikuyu pastures showing greatest values for extractable C, microbial biomass C and basal respiration at all the study sites.

The root density and depth of penetration were considerably lower under annual ryegrass than both permanent kikuyu pasture or native vegetation. A consequence of this lower root density would be lower organic matter returns to the soil. The loss of soil organic matter and aggregate stability under annually-cultivated ryegrass pasture resulted in the natural consolidation of the soil and formation of a dense surface (0 - 30 cm) layer. Consolidation may well be exacerbated by compaction caused by treading since the lower organic matter content renders the soil less resilient to compacting forces. Nevertheless, in several cases bulk density and penetrometer resistance were similar or greater under kikuyu than ryegrass pastures, suggesting that compaction has also occurred under heavy grazing of kikuyu pastures despite their higher organic matter content and greater aggregate stability.

As well as a dense surface layer, subsoil compacted layers were evident under some of the annual pastures. Cultivation with rotary cultivators to the same depth every year probably contributed to their formation. Whilst the dense, ramified root growth and large earthworm community under permanent pastures would help reform macroporosity following compaction, under annually cultivated pastures ameliorative actions such as subsoil tillage may well be necessary. At one annual pasture site, with a subsoil compacted layer, subsoiling was shown to be an effective way of decreasing bulk density and penetrometer resistance and increasing total porosity and pore continuity in both the surface layer and the subsoil compacted layer. The extent of compaction under both ryegrass and kikuyu pastures in the region needs to be examined in more detail and the effect of this on pasture growth and yields evaluated. In addition, the role of treading damage by grazing cows on such compaction needs to be determined.

Along with the decreased organic matter content under annual ryegrass pastures, there was a decrease in the soil pH and a loss of exchangeable cations, relative to permanent kikuyu pastures. Large concentrations of extractable P and exchangeable K were measured in soils in many pasture fields in the study area. These were attributed to excessive fertilizer rates (particularly P under kikuyu) and in many cases these rates could be greatly reduced. Herbage analyses highlighted various nutritional concerns, such as the need for Ca supplementation, particularly under kikuyu. The low Ca : P ratio measured in ryegrass, and more particularly in kikuyu herbage, emphasized the low Ca content of herbage and also the tendency of kikuyu grass to accumulate large concentrations of P. The large K concentrations and high K : Ca + Mg ratios recorded in a significant number of herbage samples suggests the potential for animal nutritional problems such as hypomagnesaemia. Accordingly soil K levels, particularly under kikuyu should be reduced. Although the other macro and micronutirent requirements were all generally satisfied for both pasture and nutritional requirements, Cu was, potentially limiting and fertilizer applications and/or feed supplementation are therefore required. Although kikuyu is an excellent pasture in terms of dry matter production it tends to be deficient in Ca (and sometimes Na) and can contain prohibitively high K levels, which are likely to induce Mg deficiencies in grazing animals. Feed supplements containing Ca, Mg and Na are therefore recommended particularly where kikuyu is the main feed ration.

A major problem under the system of dairy farming currently employed in the Tsitsikamma is the loss of soil organic matter, soil microbial activity and aggregates stability that occurs under annually cultivated ryegrass pastures. Annual cultivation using tractor-mounted rotary cultivators is likely to be particularly damaging to organic matter and it will also contribute to the formation of compacted subsoil layers. Because kikuyu grass is unproductive over the winter period, ryegrass pastures are required to sustain forage production over that period. Conversion from farming a seedbed by conventional tillage to direct drilling using zero tillage would seem to be a viable alternative for establishing ryegrass pastures. The resowing of ryegrass pastures on an annual basis (even when perennial ryegrass is used) is required because the pasture becomes kikuyu dominant within a year or two. Indeed, the large seedbank of kikuyu in the soils and its competitive advantage over temperate grass species means that it dominates pastures in the region. Thus using a kikuyu "base" rather than trying to eliminate it from pasture would seem to be a sensible strategy. The kikuyu-based pasture could be sprayed with a herbicide (e.g.Glyphosate), mown to ground level or perhaps burnt, prior to direct drilling ryegrass into it. A series of field trials to investigate the efficacy of such practices is warranted.

REFERENCES

Acocks, J.H.P., 1988. Veld types of South Africa. Memoirs of the Botanical Survey of South Africa. No. 57. Department of Agriculture and Water Supply.

Acton, C.J., Rennie, D.A., and Paul, E.A., 1963. The relationship of polysaccharides to soil aggregation. Can. J. Soil Sci. 43: 201-209.

Adam, G., and Duncan, H., 2000. Development of a sensitive and rapid method for the measurement of total microbial activity using fluorescein diacetate (FDA) in a range of soils. Soil Biol. Biochem., 33: 943-951.

Ahuja, L.R., Fiedler, F., Dunn, G.H., Benjamin, J.G., and Garrison, A., 1998. Changes in soil water retention curves due to tillage and natural reconsolidation. Soil Sci. Soc. Am. J., 62: 1228-1233.

Alef, K., and Kleiner, D., 1987. Arginine ammonification, a simple method to estimate microbial activity potentials in soils. Soil Biol. Biochem., 18: 233-235.

Ammermann, G.B., and Goodrich, R.D., 1983. Advances in mineral nutrition in ruminants. J. of Animal Sci., 57: 519-533.

Anderson, D.W., 1979. Processes of humus formation and transformation in soils of the Canadian Great Plains. J. Soil Sci. 30: 77-84.

Anderson, D.W., and Coleman, D.C., 1985. The dynamics of organic matter in grassland soils. J. Soil Water Conserv., 40: 211-240.

Anderson, J.P.E., 1982. Soil respiration. In: Page, A.L., (Ed.), Methods of soil analysis, part 2, 2nd ed. Soil Sci. Soc. Am. Madison, Wisconsin, pp. 837-871.

Angers, D.A., Pesant, A., and Vigneux, J., 1992. Early cropping induced changes in soil aggregation, organic matter and microbial biomass, Soil Sci. Soc. Am. J., 56: 115-.

Angers, D.A., Samson, N., and Legere, A., 1993b. Early changes in water stable aggregation induced by rotation and tillage in a soil under barley production, Can. J. Soil Sci.73: 51-59.

Anonymous., 1986. John Fair's guide to profitable pastures. Printed by; Hudson and Knight, Durban, South Africa.

Awadhwal, N.K., and Smith, G.D., 1990. Performance of low-draft tillage implements on a hard setting Alfisol of the SAT in India. Soil Use Manage., 6: 28-31.

Baldock, J.A., and Nelson, P.N., 2000. Soil organic matter. In: Sumner, M.E., (Ed.), Handbook of soil science, CRC Press Boca Raton pp. B25-B84.

Baligar, V.C., Staley, T.E., and Wright, R.J. 1991. Enzyme activities in appalachian soils: 2. Urease. Soil Sci. Plant Anal. 22: 315-322.

Baligar, V.C., and Wright, R.J. 1991. Enzyme activities in appalachian soils: 1. Arylsulfate. Soil Sci. Plant Anal. 22: 305-314

Ball, B.C., O'Sullivan, M.F., and Hunter, R., 1988. Gas diffusion, fluid flow and derived pore continuity indices in relation to vehicle traffic and tillage. J. of Soil Sci., 39: 327-339.

Barber, S.A., 1980. Soil-plant interactions in phosphorus nutrition in plants. In: Khasawnech, F.E., Sample, E.C., and Kamprath, E.J., (Eds.), The role of phosphorus in agriculture. Am. Soc. Agron. Madison, Wisconsin, pp. 591-616.

Barrow, N.J., 1987. Return of nutrients by animals. In: Snaydon, R.W., (Ed.), Managed grasslands: analytical studies, Elsevier, Amsterdam, pp. 181-186.

Bear, J., 1972. Dynamics of fluids in porus media. Elsevier Publ. Co., New York.

Beede, D.K., 1992. The DCAD concept: Transition rations for dry pregnant cows. Feedstuffs, December, 28: 12-19.

Berry, E.C., 1994. Earthworms and other fauna in the soil. In: Hatfield, J.L. and Stewart, B.A. (Eds.), Soil biology: effects on soil quality, CRC Press, Boca Raton FL, USA., pp. 61-85.

Betteridge, K., Andrews, W.G.K., and Sedcole, J.R., 1986. Intake and excretion of nitrogen, potassium and phosphorus by grazing steers. J. Agri. Sci. Camberidge, 106: 393-404.

Beven, K., and German, P., 1981. Water flow in soil macropores. A combined flow model. J. Soil Sci. 32: 15-29.

Blair, J.M., Parmelee, R.W., and Lavelle, P., 1995. Influence of earthworms on biogeochemistry. In: Hendrix, P.F., (Ed.), Earthworm ecology and biogeography in North America. Lewis Publishers, Boca Raton, pp. 127-158.

Blake, G.R., and Hartge, K.H., 1986. Methods of soil analysis. Soil Sci. Soc. Am., 9: 363-423.

Blakemore, L.C., Searle, P.L., and Daly, B.K., 1972. Methods for chemical analysis of soils. N. Z. Soil Bureau Report, 10A. Government printer, Wellington.

Blevins, R.L. and Frye, W.W., 1993. Conservation tillage: an ecological approach to soil management. Advances in Agronomy, 51: 33-78.

Bonde, T.A., Nielsen, T.H., Miller, M., and Sorensen, J., 2001. Arginine ammonification assay as a rapid index of grass mineralisation in agricultural soils. Biol. Fertil. Soils, 34: 179-184.

Bosch, D.D., and West, L.T., 1998. Hydraulic variability for two sandy soils. Soil Sci. Soc. Am. J., 62: 90-98.

Braim, M.A., Chaney, K., and Hodgson, D.R., 1984. Preliminary investigation of the response of spring barley to soil cultivation with a paraplough. Soil & Tillage Res., 4: 277-293.

Bredon, R.M., 1980. Possible factors responsible for the drop in milk production from kikuyu pasture during late summer and autumn. Natal Agricultural Research Bulletin No. 8. Department Agricultural Technical Services, Cedara, Natal.

Cambell, C.A., and Zentner, R.P., 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci. Soc. Am. J., 57: 1034-.

Cannell, R.Q. and Hawes, J.D., 1994. Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. Soil & Tillage Res., 30: 245-282.

Carter, M.R., 1986. Microbial biomass as an index for tillage induced changes in soil biological properties. Soil & Tillage Res., 7: 29-40.

Carter, M.R., 1988. Temporal variability of soil macroporosity in a fine sandy loam under mouldboard ploughing and direct drilling. Soil and Tillage Res., 12: 37-51.

Castle, M.E., and Watkins, P., 1984. Modern milk production. Faber and Faber, London Great Britain.

Chaney, K., and Swift, R.S., 1984. The influence of organic matter on aggregate stability in some British soils. J. Soil Sci., 35: 223-230.

Chen, J., and Wheater, H.S., 1999. Identification and uncertainty analysis of soil water retention models using lysimeter data. Water Resources Research, 35: 2401-2414.

Clement, C.R., and Williams, T.E., 1958. An examination of the method of aggregate analysis by wet sieving in relation to the influence of diverse leys on arable soils. J. Soil Sci. 9: 252-266.

Cluzeau, D., Binet, F., Verters, F., Simon, J.C., Riviere, J.M., Trehen, P., and Kretzschmar, A., 1992. Effects of intensive cattle trampling on soil-plant-earthworm systems in two grassland types. Soil Biol. Biochem., 24: 1661-1665.

Corey, A.T., 1986. Air permeability. In: Klute, A. (Ed), Methods of soil analysis. Part 1. 2nd edition. Agron. Monograph 9. Am. Soc .Agron. Soil Sci. Soc. Am. Madison, Wisconsin, U.S.A.

Cornforth, I.S., 1984. Mineral nutrients in pasture species. Proceedings of the N.Z. Soc. of Animal Production, 44: 135-137.

Crawford, J.W., Matsui, N., and Young, I.M., 1995. The relation between the moisture-release curve and the structure of soil. European J. Soil Sci., 46: 369-375.

Creswell, H.P., Smiles, D.E., and Williams, J., 1992. Soil structure, soil hydraulic properties and the soil water balance. Aust. J. Soil Res., 30: 265-283.

Curry, J.P., 1987. The invertebrate fauna of grassland and its influence on productivity. III., Effects on soil fertility and plant growth. Grass and Forage Sci., 42: 325-341.

Dalal, R.C., 1998. Soil microbial biomass- What do numbers really mean? Aust. J. of Experimental Agri., 38: 649-665.

Dam Kofoed, A., 1980. Copper and its utilisation in Danish agriculture. Fert. Res., 1: 63-71.

Degens, B.P., Sparling, G.P., and Abbott, L.K., 1996. Increasing the length of hyphae in sandy soil increases the amount of water-stable aggregates. Applied Soil Ecology, 3: 149-159.

Deng, S.P., and Tabatabai, M.A., 1997. Effect of crop residue management on enzyme activities in soils. III. Phosphates and arylsulphatase. Biol. Fertil Soils, 24: 141-146.

Dick, R.P., Rasmussen, P.E., and Kerle, E.A., 1988. Influence of long term residue management on soil enzyme activities in relation to soil chemical properties of wheat fallow system, Biol. Fertil. Soils, 6: 159-164.

Doran, J.W., and Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., and Stewart, B.A. (Eds.), Defining soil quality for a sustainable environment, Soil Sci. Soc. Am. Special Publication, Madison WI.

Doran, J.W. and Safley, M., 1998. Defining soil health and sustainable productivity. In: Pankhurst, C., Doube, B.M. and Gupta, V.V.S.R. (Eds.), Biological indicators of soil health, CAB International, Wallingford Oxon UK, pp. 1-29.

Doran, J.W., Sarrantonio, M. and Janke, R., 1994. Stratergies to promote soil quality and health. In: Pankhurst, C.E.,Doube, B.M.., Gupta, V.V.S.R. and Grace, P.R. (Eds.), Soil biota: management in sustainable farming, CSIRO Melbourne Australia pp. 230-237.

Doran, J.W., Sarrantonio, M. and Liebig, M.A., 1996. Soil health and sustainability. Advances in Agronomy, 56: 1-54.

Dormarr, J.F., and Pittman, U.J., 1980. Decomposition of organic residues as affected by variousdryland spring wheat fallow rotations. Can. J. Soil Sci., 60: 97-.

Drover, D.P., 1956. The influence of various rotations on coarse textured soils at Chapman and Wongan Hills research stations, western Australia. J. Soil Sci., 7: 219-244.

Drury, C.F., Stone, J.A. and Findlay, W.I., 1991. Microbial biomass and soil structure associated with corn, grasses, and legumes. Soil Sci. Soc. Am. J., 55: 805-811.

Dugmore, T.L., Lesch, S.F., and Walsh, K.P., 1987. The effect of magnesium oxide supplementation on the fertility of dairy cows grazing fertilized pastures. South Afr. J. Animal Sci., 17: 183-185.

During, C., and Weeda, W.C., 1973. N.Z. J. Agric. Res. 16: 423-430.

Eastern Cape Farming Manual, 1984. The Tsitsikamma Humansdorp Farmers Union. Dohne Agricultural Research Station. Private bag X 15, Stutterheim, 4930.

Elliot, E.T., 1986. Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J., 50: 627-.

Floate, M.J.S., 1970. Decomposition of organic materials from hill soils and pastures. Soil Biol. Biochem., 2: 173-185.

Francis, G.S., and Knight, T.L., 1993. Long term effects of conventional and no tillage on selected soil properties and crop yields in Canterbury, New Zealand, Soil and Tillage Res., 26: 193-210.

Francis, G.S., Tabley, F.J. and White, K.M., 1999. Restorative crops for the amelioration of degraded soil conditions in New Zealand. Aust. J. Soil Res., 37: 1017-10134.

Franzluebbers, A.J., Zuberer, D.A., and Hons, F.M., 1995. Comparison of microbiological methods for evaluating quality and fertility of soil. Biol. Fertil Soils, 19: 135-140.

Fraser, P.M., 1994. The impact of soil and crop management practices on soil macrofauna. In: Pankhurst, C.E., Doube, B.M.., Gupta, V.V.S.R. and Grace, P.R. (Eds.), Soil biota: management in sustainable farming, CSIRO Melbourne Australia pp.125-132.

Fraser, P.M., Francis, G.S., and Haynes, R.J., 1992. Role of management practice on earthworm populations in Canterbury soils. Efficient use of fertilizer and soil resources for tomorrow's agriculture. Proceedings of the NZIAS/NZSHS., Lincoln University.

Fraser, P.M., Haynes, R.J., and Williams, P.H., 1993. Effects of pasture improvements and intensive cultivation on size of microbial biomass, enzyme activities and compisition and size of earthworm populations., Biology and Fertility of Soils.

Fulkerson, W.J., Slack, K., Hennessy, D.W., and Hough, G.M., 1998. Nutrients in ryegrass (*Lolium* spp.), white clover (*Trifolium repens*) and kikuyu (*Pennesetum clandestinuim*) pastures in relation to season and stage of regrowth in a subtropical environment. Aust. J. Exp. Agri., 38: 22-240.

Glinski, J., and Stepniewski, W., 1983. Soil aeration and its role for plants. Boca Raton. Florida.

Goh, K.M., and Kee, K.K., 1978. Effects of nitrogen and sulphur fertilization on the digestability and chemical composition of perennial ryegrass (*Lolium perenne*, L.). Plant and Soil, 50: 161-177.

Grace, P.R., Ladd, J.N. and Skjemstad, J.O., 1994. The effects of management practices on soil organic matter dynamics. In: Pankhurst, C.E.,Doube, B.M.., Gupta, V.V.S.R. and Grace, P.R. (Eds.), Soil biota: management in sustainable farming, CSIRO Melbourne Australia pp.162-171.

Gradwell, M.W., 1967. Soil physical conditions of winter and the growth of ryegrass plants. N.Z. J. Agri. Res., 10: 425-434.

Greenwood, P.B., 1989. The effects of subsoiling on soil physical and crop production. PhD Thesis. Lincoln College, University of Canterbury, New Zealand.

Gregorich, E.G., Carter, M.R., Angers, D.A., Monreal, C.M. and Ellert, B.H., 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci., 74: 367-385.

Grunes, D.L., and Welch, R.M., 1989. Plant contents of magnesium, calcium and potassium in relation to ruminant nutrition. J. of Animal Sci., 67: 3485-3494.

Harrison, D.F., Cameron, K.C., and McLaren, R.G., 1994. Effects of subsoil loosening on soil physical properties, plant root growth and pasture yield. N.Z. J. of Agri. Res., 37: 559-567.

Haynes, R.J., 1984. Lime and phosphate in the soil-plant system. Advances in Agronomy, 37: 249-315.

Haynes, R.J., 1993. Effect of sample pretreatment on aggregate stability measured by wet sieving or turbidimetry on soils of different cropping histories. J. Soil Sci., 44: 261-270.

Haynes, R.J., 1995. Soil structural breakdown and compaction in New Zealand soils. MAF Policy Technical paper 95/5. New Zealand Ministry of Agriculture Wellington New Zealand.

Haynes, R.J., 1997. The concept of soil quality and its applicability to sugarcane production. Proc. South Afr. Sug. Technol. Ass., 71.

Haynes, R.J., 1999a. Labile organic matter fractions and aggregate stability under short-term, grass-based leys. Soil Biol. Biochem., 31: 1821-1830.

Haynes, R.J., 1999b. Size and activity of the soil microbial biomass under grass and arable management. Biol. Fertil Soils, 30: 210-216.

Haynes, R.J., 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Soil Biol. Biochem., 32 : 211-219.

Haynes, R.J. and Beare, M.H., 1996. Aggregation and organic matter storage in meso-thermal, humid soils. In: Carter, M.R. and Stewart, B.A. (Eds.), Structure and organic matter storage in agricultural soils, CRC Press, Boca Raton, Fl, USA, pp. 213-261.

Haynes, R.J. and Francis, G.S., 1993. Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. J. Soil Sci., 44: 665-675.

Haynes, R.J. and Naidu, R., 1997. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutrient Cycling in Agroecosystems, 51: 123-137.

Haynes, R.J., Swift, R.S., 1990. Stability of soil aggregates in relation to organic constituents and soil water content. J. Soil Sci. 41: 73-83.

Haynes, R.J., Swift, R.S., and Stephen, R.C., 1991. Influence of mixed cropping rotations (pasture-arable) on organic matter content, water stable aggregation and cold porosity in a group of soils. Soil and Tillage Res., 19: 77-87.

Haynes, R.J. and Williams, P.H., 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Advances in Agronomy, 49: 119-199.

He, Z.L., Alva, A.K., Calvert, D.V., and Banks, D.J., 1999. Effects of nitrogen fertilizer of grapefruit trees on soil acidification and nutrient availability in a Riviera fine sand. Plant and Soil, 206: 11-19.

Hillel, D., 1998. Environmental soil physics. Academic Press. San Diego, U.S.A.

Hogg, D.E., 1981. A lysimeter study of mineral nutrient losses from urine and dung applications on pasture. N.Z. J. Exp. Agri., 9: 39-46.

Holloway, R.E., and Dexter, A.R., 1991. Tillage and compaction effects on soil properties, root growth and yield of wheat during drought in a semi arid environment. Soil Tech., 4: 233-253.

Holmes, C.W., and Wilson, G.F., 1987. Milk production from pasture. Butterworths, Wellington, New Zealand.

Hortensius, D. and Nortcliff, S., 1991. International standardization of soil quality measurement procedures for the purpose of soil protection. Soil Use Manage., 7: 163-167.

Hutton, J.B., Jury, K.E., and Davies, E.B., 1965. N.Z. J. Agric. Res., 8: 479-496.

Hutton, J.B., Jury, K.E., and Davies, E.B., 1967. N.Z. J. Agric. Res., 10: 367-388.

Insam, H., and Domsch, K.H., 1988. Relationship between soil organic C and microbial biomass on chronosequences of reclamation sites. Microbial Ecology. 15: 177-188.

Insam, H., and Haselwanter, K., 1989. Metabolic quotient of the soil microflora in relation to plant sucession. Oecologia., 79: 174-178.

Janzen, H.H., 1987. Soil organic matter characteristics after long term cropping to various spring wheat rotations. Can. J. Soil Sci., 67: 845-.

Jenkinson, D.S., Davidson, S.A., and Powlson, D.S., 1979. Adenosine triphosphate and microbial biomass in soils. Soil Biol. Biochem., 11: 521-527.

Johnston, A.E., 1975. The Woburn market garden experiment, 1942 - 1969. II. Effects of the treatments on soil pH, soil carbon, nitrogen, phosphorus and potassium., Rothamstead Exp. Sta. Rep., 1974 Part 2: 103-131.

Johnston, A.E., 1986. Soil organic matter effects on soils and crops. Soil Use Manage., 2: 97-105.

Karlen, D.L. and Cambardella, C.A., 1996. Conservation stratergies for improving soil quality and organic matter storage. In: Carter, M.R. and Stewart, B.A. (Eds.), Structure and organic matter storage in agricultural soils, CRC Press, Boca Raton, Fl, USA, pp.395-415.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F. and Schuman, G.E., 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J., 61: 4-10.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.s. and Jordahl, J.L., 1994. Long-term tillage effects on soil quality. Soil & Tillage Res., 32: 313-327.

Kassim, G., Martin, J.P., Haider, K., 1982. Incorporation of a wide variety of organic substrate carbons into the soil biomass as estimated by the fumigation procedure. Soil Sci. Soc. Am. J., 45: 1106-1112.

Kay, B.D., 1990. Rates of change of soil structure under different cropping systems. Advances in Soil Sci., 12: 1-52.

Kazunori, S., and Oba, Y., 1994. Effect of fungal to bacterial biomass ration on the relationship between CO_2 evolution and total soil microbial biomass. Biol. Fertil Soils, 17: 39-44.

Klute, A., and Dirksen, C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (Ed), Methods of soil analysis. Part 1. Physical and mineralogical methods 2nd edition. Am. Soc. Agron. Soil Sci. Soc. Am. Madison, Wisconsin, U.S.A, pp. 687-770.

Kooistra, M.J., Lebbink, G., and Brussaard, L., 1989. The Dutch programme on soil ecology of arable farming systems. II. Geogenisis, agricultural history, field site characteristics and present farming systems at the Lovinkhoeve Experimental Farm. Agric. Ecosyst. Environ., 27: 361-.

Lal, R., 1993. Tillage effects on soil degradation, soil resilience, soil quality and sustainability. Soil & Tillage Res., 27: 1-8.

Larson, W.E., and Pierce, F.J., 1991. Conservation and enhancement of soil quality. In: Evaluation for sustainable land management in the developing world. Volume 2: International Board for Soil Research and Management, Technical papers, Bangkok, Thailand.

Ledgard, S.f., and Saunders, W.H.M., 1982. Effects of nitrogen fertilizer and urine on pasture performance and the influence of soil phosphorus and potassium status. N.Z. J. Agri. Res., 34: 105-111.

Ledgard, S.f., Steele, K.W., and Saunders, W.H.M., 1982. Effects of cow urineand its major constituents on pasture properties. N.Z. J. Agri. Res., 25: 61-68.

Lee, K.E., 1985. Earthworms, their ecology and relationships with soils and land use. Acedemic Press, New York.

Letey, J., 1985. Relationship between soil physical properties and crop production. Adv. Soil Sci. 1: 277-294.

Lightner, J.W., Rhykerd, C.L., Mengel, D.B., Van Scoyoe, G.E., Hood, E.L., and Noller, C.H., 1983. Influence of NPK fertilization on calcium and magnesium in *Poa pratensis* L. with reference to dietary requirements of grazing cattle. Communications in Soil Science and Plant Analysis, 14: 121-130.

Lipiec, J., and Simota, C., 1994. Role of soil and climate factors in influencing crop responses to soil compaction in central and eastern Europe. In: Soane, B.D., and van Ouwerkerk, C., (Eds.). Developments in agricultural engineering 11. Soil compaction in crop production. Elsevier, Amsterdam, Netherlands.

Little, D.A., 1982. Utilization of minerals. In: Hacker, J.B., (Ed.), Nutriitional limits to animal production from pastures. Division of Tropical Crops and Pastures, CSIRO, Queensland, pp. 259-279.

Lobry de Bruyn, L.A. and Kingston, T.J., 1997. Effects of summer irrigation and trampling in dairy pastures on soil physical properties and earthworm number and species composition. Aust. J. Agric. Res., 48: 1059-1079.

Lodge, R.W., 1954. Effects of grazing on the soils and forage of mixed prairie in southwestern Saskatchewan. J. Range Manage., 7: 166-170.

Low, A.J., 1954. The study of soil structure in the field and in the laboratory. J. Soil Sci., 5: 57-74.

Lynch, J.M., and Bragg, E., 1985. Microorganisms and soil aggregate stability. Adv. Soil Sci. 2:133-171.

McGarry, D., 1993. Degradation of soil structure. In: McTainish, G., Boughton, W.C., (Eds.), Land degradation processes in Australia. Longman Cheshire, Melbourne.

McGill, W.B., Cannon, K.R., Robertson, J.A., and Cook, F.D., 1986. Dynamics of soil microbial biomass and water soluble organic C in Brenton L after 50 years of cropping to two rotations, Can. J. Soil Sci., 66: 1-19.

McNaught, K.J., 1959. Effects of potassium fertilizer on sodium, amagnesium and calcium in plant tissues. N.Z. J. Agri., 99: 442-.

MacKay, A.D., and Kladivko, E.J., 1985. Earthworms and the rate of breakdown of soybean and maize residues in soil, Soil Biol. Biochem., 17: 851-857.

MacNicol, R.D., and Beckett, P.H.t., 1985. Critical tissue concentrations of potentially toxic elelments. Plant and Soil, 85: 107-129.

Manson, A.D., Milborrow, D.J., Miles, N., Farina, M.P.W., and Johnston, M.A., 1993. Explanation of the Cedara computerised fertilizer advisory service. Cedara Agricultural Development Institute. Department of Agriculture.

Marais, J.P., 1990. Effect of nitrogen on the oxalate and calcium content of kikuyu grass (*Pennisetum clandestinum* Hochst). J. of the Grassl. Soc. South Afr., 7: 106-109.

Marinho, M.C., and Igue, M., 1972. Factors affecting zinc absorption on calcite, dolomite and magnesite-type minerals. Soil Sci. Soc. Am. Proc., 20: 466-471.

Marschner, H., 1995. Mineral nutrition of higher plants 2nd edition. Academic Press, London, U.K.

Mengel, K., and Kirkby, E.A., 1987. Principles of plant nutrition, 4th edn. International Potash Institute, Worblaufen-Bern, pp. 687.

Miles, N., 1991. Nutrition of intensive pastures in the summer rainfall areas of southern Africa. J. Grassl. Soc. South. Afr., 8(2): 39-48.

Miles, N., 1998. Plant analysis criteria for pastures. Kwazulu-Natal Department of Agriculture, Cedara.

Miles, N., De Villiers, J.F., and Dugmore, T.J., 1995. Macromineral composition of kikuyu herbage relative to requirements of ruminants. J. of the S. Afr. Veterinary Association, 66: 206-212.

Miles, N., and Tainton, G., 2000. Herbage and soil characteristics of kikuyu pastures on the Eastern Cape coast. Kwazulu-Natal Department of Agriculture and Environmental Affairs and Eastern Cape Department of Agriculture.

Miller, W.J., 1979. Dairy cattle feeding and nutrition. Academic Press, New York, pp. 411.

Moodley, M., 2001. Effects of the land disposal of water treatment sludge on soil physical quality. PhD (Agric) Thesis,University of Natal.

Mudd, A.J., 1970. The influence of haevily fertilized grass on mineral metabolism of dairy cows. J. Agri. Sci. Cambridge, 74: 11-21.

Mulholland, B., and Fullen, M.A., 1991. Cattle trampling and soil compaction on loamy sands. Soil Use Manage., 7:189-193.

Naeth, M.A., Pluth, D.J., Chanasyk, D.S., Bailey, A.W. and Fedkenheuer, A.W., 1990. Soil compacting impacts of grazing in mixed prairie and fescue grassland ecosystems of Alberta. Can. J. Soil Sci., 70: 157-167.

National Research Council., 1988. Nutrient requirements of dairy cattle 6th revisevd edn. National Research Council, National Academy Press, Washington, D.C.

National Research Council., 1989. Nutrient requirements of horses 5th revisevd edn. National Research Council, National Academy Press, Washington, D.C.

Naylor, J.M., 1991. The major minerals. In: Naylor, J.M., and Ralston, S.L., (Eds.), Large animal clinical nutrition. Mosby-Year Book, St. Louis, Missouri, pp. 35-54.

Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil, 76: 319-337.

Orr, H.K., 1960. Soil porosity and bulk density on grazed and protected Kentucky Bluegrass range in the Black Hills. J. Range Manage., 13: 180-186.

Pankhurst, C.E., 1998. Biodiversity of soil organisms as an indicator of soil health. In: Pankhurst, C., Doube, B.M. and Gupta, V.V.S.R. (Eds.), Biological indicators of soil health, CAB International, Wallingford Oxon UK, pp. 297-319.

Paul, E.A., and Clark, F.E., 1996. Soil microbiology and biochemistry, 2nd edn., Academic Press, San Diego.

Paustian, K., Andren, O., Clarholm, M., Hansson, A., Johansson, G., Lagerlof, J., Lindberg, T., Pettersson, R., and Sohlenius, B., 1990. Carbon and nitrogen budgets of four agroecosystems with annual and perennial crops, with and without N fertilization. J. Appl. Ecol., 27: 60-.

Paustian, K., Collins, H.P. and Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliot, E.T. and Cole, C.V. (Eds.), Soil organic matter in temperate agroecosystems : long-term, CRC Press, Boca Raton, Fl, USA, pp. 15-49.

Parmelee, R.W., Beare, M.H., Cheng, W., Hendrix, P.F., Rider, S.J., Crossley, D.A., Jnr., and Coleman, D.C., 1990. Earthworms and enchytraeids in conventional and no tillage agroecosystems, Biol. and Fertil., Soils, 10: 1-10.

Perfect, E., Kay, B.D., van Loon, W.K.P., Sheard, R.W. and Pojasok., 1990. Factors influencing soil structural stability within a growing season. Soil Sci. Soc. Am. J., 54: 173-179.

Powlson, D.S., and Jenkinson, D.S., 1981. A comparison of the organic matter biomass, adenosine triphosphate and mineralizable nitrogen contents of ploughed and direct drilled soils. J. Agri. Sci. Cambridge, 97: 713-721.

Radcliffe, D.E., and Rasmussen, T.C., 2000. Soil water movement. In: Sumner, M.E., (Ed.). Handbook of Soil Science. CRC Press, Boca Raton. Florida.

Rasmusen, P.E., Collins, H.P., and Smiley, R.W., 1989. Long term management effects on soil productivity and crop yield in semi arid regions on eastern Oregon. Station Bulletin 675, USDA-ARS, Oregon State University.

Reason, G.K., McGuigan, K.R., and Waugh, P.D., 1989. Some consequences to dairy cattle of the addition of nitrogen fertilizers to dryland grass pastures in south-east Queensland. In: Farrell, D.J., (Ed.), Recent advances in animal nutrition in Australia 1989. Dept. Biochem. Microbiol. and Nutr., University of New England, Armidale, pp. 31-36.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil & Tillage Res., 43: 131-167.

Reid, R.L., and Jung, G.A., 1974. Effects of elements other than nitrogen on the nutritive value of forage. In: Mays, D.A., (Ed.), Forage fertilization. Am. Soc. Agron., Madison, Wisconsin, pp. 395-436.

Riekert, S., and Bainbridge, S., 1998. Analytical methods of Cedara plant laboratory. Cedara Agricultural Development Institute Department of Agriculture Kwazulu-Natal.

Roberson, E.B., Sarig, S. and Firestone, M.K., 1991. Cover crop management of polysaccharide-mediated aggregation in an orchard soil. Soil Sci. Soc. Am. J., 55: 734-739.

Roseberg, R.J., and McCoy, E.L., 1990. Measurement of soil macropore air permeability. Soil Sci. Soc. Am. J., 54: 969-974.

Roseberg, R.J., and McCoy, E.L., 1992. Tillage and traffic induced changes in macroporosity and macropore continuity: air permeability assessment. Soil Sci. Soc. Am. J., 56: 1261-1267.

Rowell, D.L., 1988. Soil acidity and alkalinity. In: Wild, A., (Ed.), Russel's soil conditions and plant growth, Longman Harlow UK., pp. 844-898.

Russell, J.S., 1986. The Human Impact. In: Russell, J.S., and Isbell, R.F., (Eds.), Australian soils, University of Queensland Press, St. Lucia, Queensland Australia., pp.374-396.

Russell, J.S., and Williams, C.H., 1982. Biogeochemical interactions of carbon, nitrogen, sulphur and phosphorus in Australian agroecosystems. In: Galbally, I.E., and Freeney, J.R., (Eds.), The cycling of carbon, nitrogen, sulphur and phosphorus in terresrtial and aquatic ecosystems. Soil Biol. Biochem., 21: 759-765.

Saeed, M., and Fox, R.L., 1979. Influence of phosphorus fertilization on zinc adsorption by tropical soils. Soil Sci. Soc. Am. J., 43: 683-686.

Safaya, N.M., 1976. Phosphorus-zinc interaction in relation to absorption rates of phosphorus, zinc, copper, manganese and iron in corn. Soil Sci. Soc. Am.J., 40: 719-722.

Salette, J., 1978. Sulphur content in grasses during primary growth. In: Brogan, J.C., (Ed.), Sulphur in forages. An Foras Taluntais, Dublin, pp.142-152.

Sauerbeck, D.R., 1982. Influence of crop rotation, manurial treatment and soil tillage on the organic matter content of German soils. In: Boels, D., Davies, D.B., and Johnston, A.E., (Eds.), Soil degradation. Proceedings of the EEC seminar held in Wageningen, Netherlands, pp. 163-179.

Schnitzer, M., 1986. Binding of humic substances by soil mineral colloids. In: Huang, P.M., and Schnitzer, M., (Eds.), Interactions of soil minerals with natural organics and microbes, SSSA Spec. Pub. 17. Soil Sci. Soc. Am., Madison, WI.

Schnürer, J., Clarholm, M., and Rosswall, T., 1985. Microbial biomass and activity in agricultural soil with different organic matter contents, Soil Biol. Biochem., 17: 611-618.

Schnürer, J., and Rosswall, T., 1982. Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil and litter. Applied Environmental Microbiology., 43: 1256-1261.

Schulze, R.E., Hutson, J.L., and Cass, A., 1985. Hydrological characteristics and properties of soils in Southern Africa 2: Soil water retention models. Water South Afr., 11: No.3.

Sears, P.D., and Evans, L.T., 1953. Pasture growth and soil fertility. III The influence of red and white cover, superphosphate, lime, and dung and urine on soil composition and on earthworm and grass grub populations. N.Z. J. Sci. Tech., 35A, Supplement 1: 42-52.

Sheath, G.W. and Carlson, W.T., 1998. Impact of cattle treading on hill land: Soil damage patterns and pasture status. N.Z. J. of Agricultural Res., 41: 271-278.

Seybold, C.A., Mausbach, M.J., Karlen, D.L. and Rogers, H.H., 1998. Quantification of soil quality. In: Lal, R. *et al.*, (Eds.), Soil processes and the carbon cycle, CRC Press, Boca Raton, FL, USA, pp.387-405.

Seybold, C.A., Herrick , J.E. and Brejda, J.J., 1999. Soil resilience: a fundamental component of soil quality. Soil Sci.,164: 224-234.

Singleton, P.L. and Addison, B., 1999. Effects of cattle treading on physical properties of three soils used for dairy farming in the Waikato, North Island, New Zealand. Aust. J. Soil Res., 37: 891-902.

Smith, P., and Thomasson, J., 1974. Density and water-release characteristics. In : Avery, B.W. and Bascomb, C.L., (Eds.). Soil survey laboratory methods. Tech. Monograph No. 6. Rothamstead Experimental Station. Harpendon. Herts.

Smith, J.E., Robin, M.J.L., and Elrick, D.E., 1998. Improved transient flow air permeameter design: dampening the temperature effects. Soil Sci. Soc. Am. J., 62: 1220-1227.

Soil Classification Working Group., 1991. *Soil Classification*: A Taxonomic System for South Africa. Memoirs on the Agricultural Natural Resources of South Africa. No. 15. Department of Agricultural Development. Pretoria.

Sollins, P., Homan, P., and Caldwell, B.A., 1996. Stabilisation and destabilisation of soil organic matter: mechanisms and controls. Geoderma, 36: 201-214.

Spain, A., 1990. Influences of environmental conditions and some soil chemical properties on the ınd nitrogen content of some Australian rainforest soils. Aust. J. Soil Res., 28: 825-839.

ȝ, G.P., 1985. The soil biomass. In: Vaughan, D., and Malcolm, R.E., (Eds.), Soil organic ınd biological activity, Martinus Nijhoff, The Hague, pp. 223-262.

ȝ, G.P., 1992. Ratio of microbial biomass carbon to soil organic carbon as a sensetive ›r of changes in soil organic matter. Aust. J. Soil Res., 30: 195-207.

g, G.P., 1997. Soil microbial biomass, activity and nutrient cycling as indicators of soil In: Pankhurst, C., Doube, B.M. and Gupta, V.V.S.R. (Eds.), Biological indicators of soil CAB International, Wallingford Oxon UK, pp. 97-119.

G., and Godwin, R.J., 1978. An experimental investigation into the deep looseing of soil tines. J. Agri. Eng. Res., 23: 243-258.

, D.A., and Burger, R.T., 1967. Availability to plants of zinc sorbed by soil and hydrous Geoderma, 1: 13-17.

wski, W., Glinski, J., and Ball, B.C., 1994. Effects of compaction on soil aeration ies. In: Soane, B.D., and van Ouwerkerk, C., (Eds.). Developments in agricultural ring 11. Soil compaction in crop production. Elsevier, Amsterdam, Netherlands.

son, F.J., 1994. Humus chemistry : genesis, composition, reactions. John Wiley & Sons, 5 Third Avwnue, New York., pp. 15-18.

I.A. and Buttery, B.R., 1989. Nine forages and the aggregation of clay loam soil. Can. J. i., 69: 165-169.

ıholtz, D.D., Olsen, R.J., Gogan, G., and Olson, R.A., 1966. On the mechanism of orus-zinc interaction in corn nutrition. Soil Sci. Soc. Proc., 30: 759-763.

g, F.E.T., 1975. Pasture management trials on unploughable hill country at Te Awa. III.

Results for 1959-1969. N.Z. J. Exp. Agri., 3: 351-336.

Tate, R.L., 1995. Soil microbiology. John Wiley, New York.

Thurston, J.M., Williams, E.D., and Johnston. A.E., 1976. Modern developments in an experiment on permanent grassland started in 1856: effects of fertilizers and lime on botanical composition and crop and soil analyses, Ann. Agron., 27: 1043-.

Tisdall, J.M. and Oades, J.M., 1979. Stabilisation of soil aggregates by the root systems of ryegrass. Aust. J. Soil Res., 17: 429-441.

Tisdall, J.M., and Oades, J.M., 1982. Organic matter and water stable aggregates in soils. J. soil Sci. 33: 141-163.

Tyson, K.C., Roberts, D.H., Clement, C.R., and Garwood, E.A., 1990. Comparison of crop yields and soil conditions during 30 years under tillage or grazed pasture. J. Agri. Sci., 115: 29-.

Underwood, E.J., and Suttle, N.F., 1999. The mineral nutrition of livestock 3rd edn. CAB International, Wallingford, Oxon, U.K.

Unger, P.W., 1996. Soil bulk density, penetration resistance and hydraulic conductivity under controlled traffic conditions. Soil & Tillage Res., 37: 67-75.

Vance, E.D., Brookes, P.C., and Jenkinson, D.C., 1987. An extraction method for measuring microbial biomass C. Soil Biol. Biochem., 19: 703-707.

Vitosh, M.L., Lucas, R.H., and Silva, G.H., 1997. Long term effects of fertilizer and manure on corn yield, soil carbon and other soil chemical properties in Michigan. In: Paul, E.A., Elliott, E.T., Paustian, K., and Cole, C.V., (Eds.), Soil organic matter in temperate agroecosystems, CrC Press, Boca Raton, Florida, USA., pp.129-140.

Wardle, D.A., 1992. A comparative assessment of factors which influence microbial biomass carbon and nitrogen levels in the soil. Biol. Rev., 67: 321-358.

Wardle, D.A., and Ghani, A., 1995. A critique of the microbial metabolic quotient (qCO_2) as a bioindicator of disturbance and ecosystem development. Soil Biol. Biochem., 27: 1601-1610.

Watson, K.W., and Luxmoore, R.J., 1986. Eatimating macroporosity in a forest watershed by use of a tension infiltrometer. Soil Sci. Soc. Am. J., 50: 578-582.

Weeda, W.C., 1977. Effects of cattle dung patches on soil tests and botanical and chemical composition of herbage. N.Z. J. of Agri. Res., 20: 471-478.

Whitehead, D.C., 2000. Nutrient elements in grassland : soil-plant-animal relationships. CAB International, Wallingford Oxon.

Wiersum, L.K., 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant Soil, 9: 75-85.

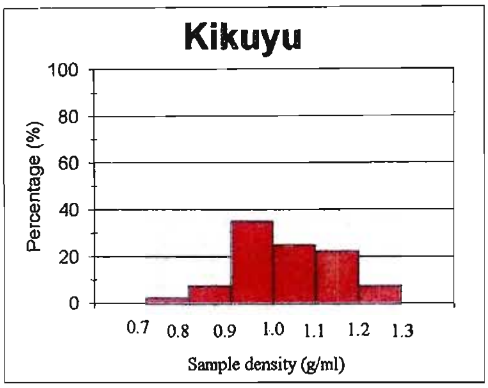
William, J., 1977. Compaction of soil by agricultural equipment. Division of Agricultural Sciences University of California, Bulletin 1881.

Williams, P.H., Gregg, P.E.H., and Hedley, M.J., 1989. Uptake of potassium and nitrogen by pasture from urine affected soil. N.Z. J. Agri. Res., 32: 415-421.

Williams, P.H., Gregg, P.E.H., and Hedley, M.J., 1990. Fate of potassium in dairy cow urine applied to intact soil cores. N.Z. J. Agri. Res., 33: 151-158.

Wood, M., 1995. Biological processes in soil. In: Environmental Soil Biology 2nd ed. Blackie Academic, London, pp 41-65.

APPENDIX 1


Kikuyu
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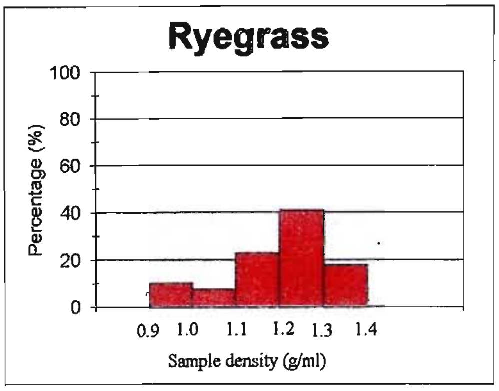
60
40
20
0
Percentage (%)
0.7 0.8 0.9 1.0 1.1 1.2 1.3
Sample density (g/ml)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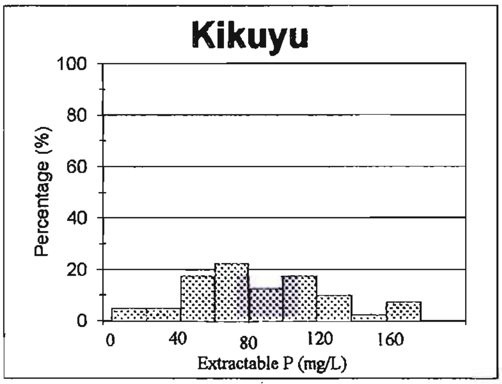
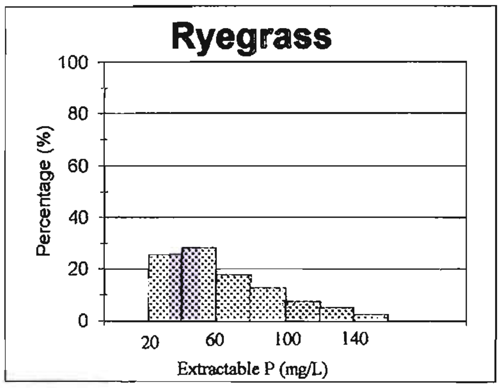
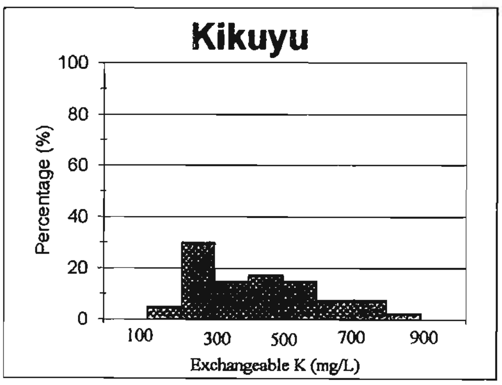
80
60
40
20
0
Percentage (%)
0.9 1.0 1.1 1.2 1.3 1.4
Sample density (g/ml)


Kikuyu
100
80
60
40
20
0
Percentage (%)
0 40 80 120 160
Extractable P (mg/L)


Ryegrass
100
80
60
40
20
0
Percentage (%)
20 60 100 140
Extractable P (mg/L)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80
60
40
20
0
Percentage (%)
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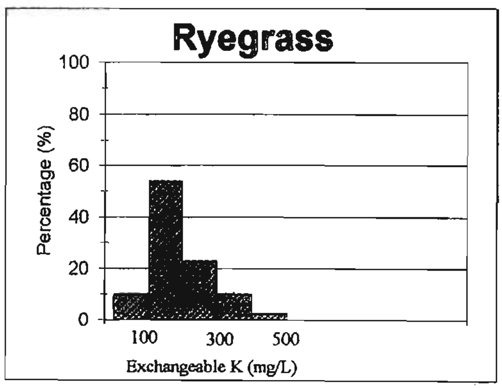
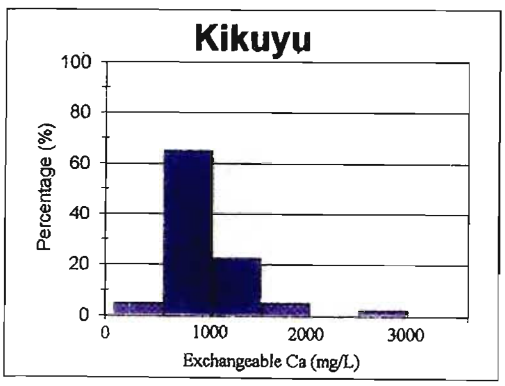
Exchangeable K (mg/L)


Ryegrass
100
80
60
40
20
0
Percentage (%)
100 300 500
Exchangeable K (mg/L)


Kikuyu
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80
60
40
20
0
Percentage (%)
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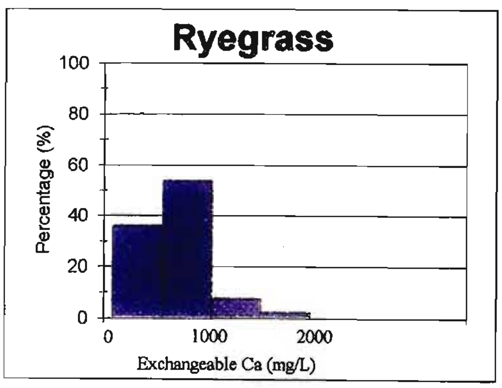
Exchangeable Ca (mg/L)


Ryegrass
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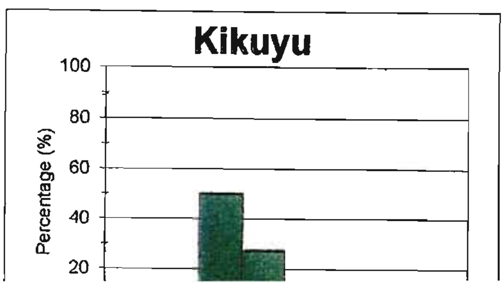
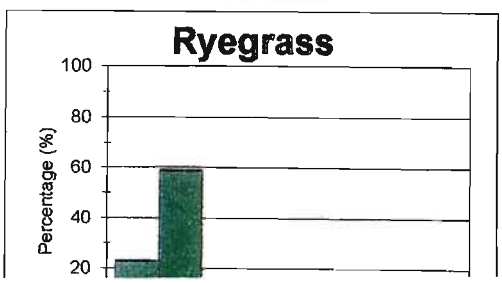
80
60
40
20
0
Percentage (%)
0 1000 2000
Exchangeable Ca (mg/L)


Kikuyu
100
80
60
40
20
Percentage (%)


Ryegrass
100
80
60
40
20
Percentage (%)