PASTURE GROWTH CONSTRAINTS ON DRY STEEP EAST COAST HILL COUNTRY

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ABSTRACT

Dry hill country provides a diverse environment in which variations in aspect and slope affect pasture growth and soil processes in a number of different ways.

The AgResearch fertiliser and pasture growth trial at Waipawa in the east coast of the North Island of New Zealand, provided an ideal location, with contrasting topography and fertiliser treatments at which to measure pasture growth constraints, with particular reference to nitrogen (N), in dry east coast hill country over the period of a year.

Initial soil testing at the trial site revealed large differences in soil total N and phosphorus (P) concentrations between aspects, slopes and P fertility regimes in the top 75 mm of the Waipawa silt loam soil. The measured differences in soil N concentrations (ranging from 2.60-5.80 mg N/g) are a result of contrasting energy and moisture regimes between the aspects and slopes, affecting soil forming processes and subsequent soil total N concentrations. The differences in soil total P concentrations (ranging from 0.42-0.88 mg P/g) between aspects and slopes can be largely attributed to stock transfer, while the variation between P fertility regimes can be attributed to a large application of P fertiliser to the high P treatment before commencement of the trial.

The existing trial provided three main contrasts over which the major restrictions on pasture growth could be measured. These were phosphate status (high phosphate (HP) and low phosphate (LP)), aspect (North and South), and slope (steep (25° +), easy (15-20°) and flat (0-12°)). This gave a total of ten combinations of P status and topography. Each of these sites was replicated three times to give a total of 30 locations. At each location two 0.5 m^2 cages were used to measure pasture growth. One of the cages was used to measure pasture growth under the current soil fertility regime, while the other cage had 120 kg N/ha as urea applied to it, to allow growth under non-limiting N conditions. The cage locations were pretrimmed before cage placement and pasture was cut monthly (or when growth conditions permitted) and analysed. Soil samples were taken from adjacent to the cage under which pasture growth was measured in the absence of added N fertiliser. Each sample comprised six cores that were taken to a depth of 75 mm at the start of each growth period and analysed for a range of soil measurements, which were related to pasture growth.

There was a wide range of total pasture yield and pasture growth rates between sites and seasons. Measured total annual pasture production ranged from 2394 – 9067 kg DM/ha/yr in the absence of added N on HP northerly steep (HPNS) and HP northerly easy (HPNE) sites respectively. Total annual pasture production in the presence of non-limiting N (potential yield) ranged from 8001 – 18532 kg DM/ha/yr on LP northerly steep (LPNS) and HPNE sites respectively. Daily pasture growth rates in the absence of added N ranged from 1.13 kg DM/ha/day on the LPNS sites in mid spring to 34.51 kg DM/ha/day on HP southerly easy (HPSE) sites in the same period. Daily pasture growth rates in the presence of non-limiting N ranged from 3.78 kg DM/ha/day on LPNS sites in mid spring to 77.95 kg DM/ha/day on the HPNE sites in early spring.

The major constraints on pasture growth within each site fluctuated throughout the year, between climatic and nutrient inputs. However, the most consistent and major constraint on all sites was N deficiency. Total annual pasture yield depression from potential due to N deficiency ranged from 5757 – 9465 kg DM/ha/yr on LPNS and HPNE sites. Daily pasture yield depression from potential growth rate ranged from 2.65 kg DM/ha/day on LPNS sites in mid spring to 45.36 kg DM/ha/day on HPNE sites in early spring.

Increased P levels provided increased total annual yields, with HP sites yielding on average 1038 and 2209 kg DM/ha/yr more pasture in the absence and presence of non-limiting N respectively than LP sites. NE and flat sites produced the largest and most consistent P responses throughout the year, whilst the P response was generally largest in dry periods when soil moisture was limiting. This was suggested to result from an increased rooting depth on HP sites allowing them to source more water.

Sunlight and temperature were major constraints on pasture growth on southerly and flat sites throughout late autumn and winter, whilst soil moisture was the major constraint on northerly sites from mid spring through to the end of summer as well as on southerly and flat sites from mid to late summer.

Clover yields were small and scattered throughout the trial in all seasons. The HPNE and HPSE sites generally yielded the most clover throughout the year, with the highest yield of 1497 kg DM/ha/yr measured on HPNE sites in the presence of non-limiting N.

The mineralisable N soil test showed some potential for use as an indicator of potential pasture yield, however the varying temperature regimes between aspects and slopes limited its applicability to all sites due to the heavy dependence of the mineralisation rate on temperature. The Olsen P and ammonium-N and nitrate-N soil tests provided no significant relationship with pasture yield.

A pasture growth model relating pasture growth (G) to evapotranspiration (E_t) according to the equation $G = kE_t$ (where the proportionality constant (k), with units of kg D.M./ha/mm, is a site-specific factor which could be an index of soil fertility status), showed potential to be used in hill country.

The model was able to account for much of the greater than two fold difference in total annual pasture yields between the lowest producing and highest producing sites in the presence of non-limiting N ($R^2 = 0.66$), using a single growth constant (k) for LP and HP sites. When separate k values were used for LP and HP sites the relationship between measured and predicted total annual yield improved ($R^2 = 0.89$ & 0.73 for LP and HP sites respectively). When the seasonal accuracy of the model was tested, prediction on some sites in some periods was found to be inaccurate. Some simple adjustments such as altering the depth of available water and winter growth rates on southerly steep (SS) sites was able to increase the accuracy of the model on some of the sites. Major factors decreasing the accuracy of the model appear to be depth of available water, soil hydrophobicity in summer, recharging of soil water through capillary action in spring and warm convection currents increasing pasture growth on SS sites in winter to above predicted levels. Further development of the model will require the effect of these factors to be quantified and accounted for.

The model was also able to reasonably accurately predict the soil gravimetric water contents (top 75 mm) of sites of contrasting aspect and slope over a four year period.

Overall, dryland hill country provides an extremely variable pasture production system which is affected by a great number of factors. The greatest factor affecting pasture growth appears to be plant available N, which in dryland hill country is inherently severely deficient. The other major factors are mostly climate-related and vary between sites depending on aspect and slope location. The intensification of farming systems demands that these variations can be accurately accounted for so that more accurate whole farm system models can be used to develop farming policy and economic models. Calculating E_t and the subsequent depression from maximum yield by soil fertility, appears to be a method by which future models may more accurately aid farmers in analysing the efficiency of their system.

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CHAPTER 1

INTRODUCTION

There is ever-increasing economic and environmental pressure on New Zealand's hill country farmers to improve the efficiency of their fertiliser use. However, optimising the nutrient management of grazed hill country pastures is an exceedingly complex task – much more complex than for traditional broad-scale cropping systems.

This complexity arises in part because of the variable terrain and the associated patterns of animal grazing and excretal return. But the largest contributor to the complexity is the use of legumes, such as clover, to supply atmospheric nitrogen (N) to the sward – rather than relying on fertiliser N, as is the case in most cropping systems. Fertilisers are used to provide sufficiently high levels of plant-available, macro- and micro-nutrients (such as phosphorus (P), sulphur (S), potassium (K) and molybdenum (Mo)) to enable the clover plants to compete successfully with the more vigorous grass species and fix N.

Throughout most of New Zealand this approach has provided cost-effective forage for associated animal production. However, it has long been recognised that relying solely on N fixed by legumes, places a major constraint on the levels of pasture production that can be achieved. This constraint arises in two ways.

- On an annual basis, the amounts of N that can be fixed by legumes under realistic farming conditions are too low to support the most highly productive livestock systems.
- On a seasonal basis, there is often a mismatch between the rate at which N is made available from soil organic N by mineralisation, and the rate at which it could potentially be taken up by the grass species in the sward.

These constraints are particularly evident in summer-dry hill country. In these dry climates, pasture legume content is generally low, and in the summer months, non-existent on the driest sites. This lack of legume growth reduces the amount of nitrogen that is entering the pastoral system, and this in turn limits pasture growth.

In recognition of the chronic under-supply of N in New Zealand pastures there has been ongoing interest in the response of mixed-sward pastoral systems to additions of fertiliser N by many workers, including O'Connor and Gregg (1971), Scott (1972), Ball *et al.* (1976), Ball *et al.* (1978), Carran (1979), Luscombe (1980), Ledgard *et al.* (1983), Lambert and Clark (1986), Wedderburn *et al.* (1990), Nie *et al.* (1998) and others.

Most of this interest has centred on flat-land, intensive systems, particularly dairy farms, in which fertiliser N is used tactically, to supplement the supply of N fixed by legumes and overcome seasonal shortfalls in pasture supply.

Increasingly however, farmers are extending this use of N fertiliser into more extensive hill country farming operations. This recognises that in areas where topography and climate make legume growth difficult, the creation of high levels of soil fertility to support legume establishment may be difficult to justify. This may be particularly the case in areas where phosphorus (P) runoff into surface waters is of environmental concern

A more profitable and environmentally sustainable approach may be to apply low rates of P, S and other nutrients, to balance losses from the system, and to plan strategically to use N fertiliser at the most opportune times to optimise animal production. Before such an approach is adopted on a wide scale however, there needs to be in-depth research on the relative agronomic and economic advantages of N and/or P fertiliser use in dry hill country.

This introduces another facet of the complexity of grazed pasture systems – namely the prediction of the growth response to the addition of P (and other) fertilisers. In cropping systems it is a relatively simple matter to identify critical soil test levels and generate response curves for added fertilisers. In legume-based pastures however, addition of P fertilisers may overcome a P deficiency present in the grass component of the sward, but it is also likely to stimulate additional clover growth. This, in turn, increases the N inputs to the system and further boosts grass growth.

This secondary effect of P fertiliser addition on N supply is likely to be much greater than the initial alleviation of a P deficiency. But the magnitude and timing of this additional N response is highly dependent on climate and topography. This makes it very difficult to generate quantitative pasture response curves based solely on soil test (e.g. Olsen P) levels, for use in decision support models.

Although traditional soil tests will continue to have a valuable role in grazed pastures, to identify nutrient deficiencies and monitor nutrient levels over time, a new approach to quantitatively predicting the size of fertiliser responses is urgently required. Such an approach must take into account the effects of topography and climate on pasture growth.

Fortunately, new technologies such as GIS and Remote Sensing enable much more precise description of land-form. Climate data are also increasingly available in digital form, ready for direct inclusion in computer models. To make use of these new technologies however, requires an in-depth understanding of those factors affecting pasture growth in hill country.

The objective of this study was to gain an improved understanding of those environmental and soil factors controlling pasture growth on summer-dry hill country and to then use this understanding to evaluate an alternative approach to modeling pasture production.

CHAPTER 2

LITERATURE REVIEW

2.1 DRYLAND HILL COUNTRY FARMING SYSTEMS

2.1.1 Introduction

Dryland hill country is characterised by low annual rainfall (< 900 mm/yr) with a regular dry summer-autumn. The effects of low rainfall are modified by variable slopes, differences in aspects and variability in soil depth and type. On steep slopes soils are often shallow, resulting in an increased risk of drying out and problems of erosion, due to slipping and slumping (Grant *et al.,* 1973). Most hill country soils are of low fertility, which results in them supporting grass species of low quality. Subsequently, pasture growth is severely limited by these factors (Gillingham, 1974; Lambert *et al.,* 1982). Because of the steepness of slope, most hill country cannot be cultivated and consequently improvements in pasture species and production must be brought about by oversowing and other management practices (Grant *et al.,* 1973).

2.1.2 Characteristics of Dryland Hill Country

2.1.2.1 Stock

Due to the dry nature and low productivity of dryland hill country in comparison to lowland farms, sheep and beef farming predominates (Ball *et al.,* 1982). Breeding ewes for production of store lambs are farmed across the broad range of moderate to steep hill country, while cattle are mainly confined to flats or moderate slopes. The average stocking rate for dry hill country is about seven ewes per hectare or one breeding cow per hectare (AgResearch Bulletin, 1997).

2.1.2.2 Climate

Within New Zealand, the areas in which dryland hill country farms exist include the east coast of both the North and South Islands and Central Otago. The climate within these areas consists mainly of wet, mild winters and hot, dry summers, with variably wet and dry autumns and springs (Chapman and MacFarlane, 1985). Annual rainfall within these areas varies from about 650 mm in Marlborough in the north of the South Island to about 900 mm in Hawkes Bay on the east coast of the North Island (Kerr *et al.,* 1986).

2.1.2.3 Slope and Aspect

Variability of slope and aspect is a characteristic of all hill country and results in a wide and diverse range of habitats with varying edaphic and biotic characteristics (Lambert and Roberts, 1976). The variation between the many habitats can be attributed to the difference in micro-climatic factors caused by topographic differences. The contrasting aspects give distinctively different micro-environments. Seasonal temperature and moisture regimes vary markedly between warmer north-facing slopes and cooler south-facing slopes (Gillingham, 1974; Lambert and Roberts, 1976). This results in greater winter production on the northerly-facing slopes, while summer pasture production on cooler faces frequently exceeds that on warmer faces (Suckling, 1975). The soils on steeper slopes are generally more shallow and have a reduced water holding capacity, which combined with less effective rewetting, results in more and longer soil moisture deficits (Sheath and Broom, 1985 ; De Rose *et al.,* 1995).

Other authors have also found many differences in physical properties between aspects. Rumball (1966) and Radcliffe (1968) detected differences in the moisture content of north- and south-facing soils. Suckling (1954, 1959, 1975) recorded temperature differences between aspects. Jackson (1967) and McAneney and Noble (1976) calculated differences in net radiation and potential evapotranspiration, and Yates (1970) and Jackson and Aldridge (1972) recorded differences in rainfall between aspects.

2.1.2.4 Soil Fertility

Hill country soils are renowned for their poor fertility. Nitrogen (N) deficiency is the principal nutrient limitation to pasture growth. Most hill country farms rely on inputs of N from legumes which fix N from the atmosphere, and transfer it to grasses through herbage death and decay, or through animal excreta. However, legume growth is limited by low phosphorus and sulphur status, and so single superphosphate is the most widely applied fertiliser to hill country (Chapman and Macfarlane, 1985). A more in-depth review of nitrogen fixation is presented in Section 2.3.4.

2.1.2.5 Grazing Management

Many dryland hill country farms are set stocked for much of the year. Paddocks are often too large for more intensive grazing systems (Ball *et al.,* 1982). However, the more intensively-farmed units have greater subdivision to allow rotational grazing management. Dry hill country can have large seasonal differences in growth rates. Radcliffe (1975) measured growth rates ranging from 3.5 kg D.M./ha/day in winter to 39.4 kg D.M./ha/day in spring. In summer, pasture growth regularly ceases completely. This, combined with the set stocking regime, means that pasture production is limited by two extremes.

1. Under-grazing (lax grazing pressure) at times of the year when pasture production is at its highest. This allows dead material to accumulate, shading out clovers and reducing pasture density.

2. Over-grazing (severe grazing pressure) at times of the year when pasture production is at its lowest. This also reduces pasture density and exposes bare areas for weed invasion (Chapman and Macfarlane, 1985).

2.1.2.6 Pasture composition

Dryland hill country pastures vary greatly in composition. Climate and soil fertility are the major factors affecting the botanical composition of the swards (Levy, 1970). Unimproved hill country swards characteristically contain a wide array of grass species such as browntop (*Agrostis capillaris*), yorkshire fog (*Holcus lanatus*) and sweet vernal (*Anthoxathum odoratum*), a few, poorly productive legumes, like subterranean clover (*Trifolium subterraneum*) and a variety of weeds (Grant *et al.,* 1973). Improved hill country pastures contain an increased amount of ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). However, the poor phosphorus fertility and the dry nature of the many hill country soils restrict clover growth and subsequently ryegrass production (Suckling, 1959; 1975). In general, dry hill country pastures are characterised by low legume content because of the regular summer dryness when legumes are usually growing most actively.

2.2 FERTILISER USE IN NEW ZEALAND

Fertiliser has been a key part of New Zealand agriculture since the early 1880's when it was realised that phosphorus (P) was an important nutrient in the development of legume based pastures. The Canterbury Agricultural College at Lincoln first imported superphosphate in 1880, a year before commercial production of superphosphate commenced in Dunedin (Duncan, 1994). From then through to the present day single superphosphate (SSP) has been the most common form of fertiliser used. The SSP was manufactured from the acidulation of phosphate rock sourced from the Indian and Pacific Oceans and provided the P and sulphur (S) requirements of most New Zealand pastures (Faulalo, 1997).

The dominance of SSP fertilisers was a result of a number of factors- the first being that N is a nutrient that is provided “free” through fixation by leguminous pastures. This meant that by the application of one fertiliser (SSP), the farmer was effectively gaining an additional nutrient, due to the subsequent increased legume growth.

Another factor was that P can be considered a "money in the bank" nutrient, as it is not easily lost from the plant-soil system (except by crop removal). Applications of SSP fertiliser at above-maintenance levels therefore increase soil P status, and the residual effects of SSP application are apparent over a long period. Nitrogen and S are nutrients easily lost through leaching from the soil-plant system and so, if they are not quickly taken up by plants, the fertiliser can be wasted.

Until the development of the urea manufacturing plant at Kapuni in 1983, N fertilisers were expensive and relatively unavailable (Douglas and Cochrane, 1989). Since that time, N fertiliser costs have remained relatively high but are less subject to international exchange rate variations.

Due to a downturn in the rural economy, and the removal of subsidies by the government in 1986, there was a reduction in overall fertiliser use. In the late 1980's, fertiliser use was only about 50-65% of that in the late 1970's (Faulalo, 1997). This trend has been reversed since the early 1990's when the dairying sector started to experience increased profits, resulting in increased fertiliser use. More recently, the trend has continued with the sheep and beef industry receiving increased profits in recent years.

Along with an increase in fertiliser use in the dairying industry, there has also been a change in the type of fertiliser use. In the early 1980's, SSP represented about 95% of the total fertiliser sales. This had fallen to 75% by 1993, due largely to increased use of N fertilisers and an increased use of high analysis fertilisers (MAF Agriculture Policy, Wellington, 1994).

2.2.1 Environmental impact of fertiliser use.

As fertiliser usage has changed over the years so has the awareness of the environmental implications of this fertiliser usage. Where environmental issues are concerned the two major types of fertiliser that are problematic are phosphatic and nitrogenous fertilisers.

The application of phosphatic fertilisers can potentially create two major environmental problems. The first is eutrophication of waterways. It is generally considered that P is the major nutrient governing eutrophication (Sharpley and Rekolainen, 1997). One of the mechanisms by which P enters waterways is through surface runoff from agricultural land, in which P is transported in sediments and in soluble forms. The application of phosphatic fertilisers can increase the amount of P in surface runoff and subsequently increase eutrophication (Blennerhassett, 1998). The second area of concern in relation to phosphatic fertiliser addition, is the accumulation of cadmium (Cd) in soils. Cadmium is a heavy metal that is potentially toxic to both humans and animals, and accumulates in pasture as a result of phosphatic fertiliser addition (Bramley, 1990).

Like P, nitrogenous fertilisers are of environmental concern for two major reasons. The first area is soil acidification. Soil acidification is increased firstly by the process of nitrification, which occurs as a result of using urea and ammonium fertilisers. Acidification is also increased through the leaching of nitrate (Bolan, *et al.,* 1989). Nitrate leaching is increased by using nitrogenous fertilisers, but more particularly by grazing animals concentrating N in urine spots (Ledgard *et al.*, 1997).

The increased nitrate leaching caused by the use of nitrogenous fertilisers and grazing animals is the second area of concern. Nitrate leaching increases groundwater nitrate contamination, which may be associated with human and stock health problems (Selvaraj *et al.,* 1994).

2.3 NITROGEN IN SOILS

2.3.1 Introduction

Nitrogen occupies a unique position among the elements essential for plant growth because of the large amounts required by most agricultural crops. This has meant that N has been studied extensively in relation to its forms and transformations within the soil system. Soil is one the most complex systems within our world, from not only a biological, but also chemical and physical viewpoints. The complexity of this system means that to gain a full understanding of N forms and interactions in soil, the system must be broken down into the individual pathways of the many different forms of N. This section gives an overview of the various forms of N in soil and the many transformations it undergoes.

2.3.2 Geochemistry of nitrogen

Nitrogen is of geological interest because of its occurrence in the four recognised spheres of the earth, namely, lithosphere, atmosphere, hydrosphere and biosphere. The significance arises because the air over every square meter of the earth contains 30000 kg of N. After carbon, hydrogen and oxygen, no other element is so intimately associated with the reactions carried out by living organisms (Stevenson, 1982a).

The approximate inventory of the four spheres is given in Table 2.1. The bulk of the N is in the lithosphere (98 %), and most of the remainder is in the atmosphere. Molecular N_2 comprises about 78% of the gases in the atmosphere. Other N compounds in the atmosphere found in minute amounts include ammonium, nitrate, nitrous oxide and organically bound N, associated with terrestrial dust (Stevenson, 1982a).

The figure of 2.8×10^5 Tg of N in the biosphere is an approximation at best. This uncertainty is due to the fact that the biosphere is in a constant state of flux, and matter within the biosphere is unevenly distributed (Stevenson, 1982a).

In the hydrosphere, N occurs as molecular N_2, ammonium, nitrite, nitrate and dissolved and particulate organic matter. Molecular N_2 is the dominant form, accounting for 95% of the total. Variations in abundance of the different forms of N occur with depth, season, biological activity and other factors, but in the long run the amount of each remains constant (Emery *et al.*, 1955).

Nitrogen is a common component of the lithosphere (soils, sediments, silicate minerals, fossils and rocks of all types). Most of the N occurs in association with igneous rocks of the earth's crust and mantle, possibly as ammonium held within the lattice structures of such primary silicate minerals as the micas and feldspars (Stevenson, 1965).

Table 2.1 Inventory of N in the four spheres of the earth. All values are in terrograms (1 terrogram = million metric tons). Table taken from Stevenson (1982a).

Sphere	**Tg of N**
Lithosphere	1.636×10^{11}
Igneous rocks	
a) of the crust	1.0×10^{9}
b) of the mantle	1.62×10^{11}
Core of the earth	1.3×10^{8}
Sediments (fossil N)	$3.5\text{-}5.5 \times 10^{8}$
Coal	1.0×10^{5}
Sea bottom organic compounds	5.4×10^{5}
Terrestrial soils	
a) Organic matter	2.2×10^{5}
b) Clay fixed NH_4^+	2.0×10^{4}
Atmosphere	3.86×10^{9}
Hydrosphere	2.3×10^{7}
Biosphere	2.8×10^{5}

2.3.3 Inorganic forms of nitrogen in soil

There are seven inorganic forms of N found in soils. These include nitrate (NO_3^-), nitrite (NO_2^-), exchangeable ammonium (NH_4^+), nonexchangeable (mineral-fixed) ammonium (NH_4^+), dinitrogen gas (N_2), ammonia gas (NH_3) and nitrous oxide (N_2O) (Young and Aldag, 1982). These can be divided into three main categories, - exchangeable and water soluble forms, nonexchangeable nitrogen, and soil nitrogen gases.

2.3.3.1 Exchangeable and water soluble forms

Nitrate, nitrite and exchangeable ammonium are the three forms which make up the exchangeable and water soluble category. These three forms are consequently plant available, with NO_3^- and NH_4^+ providing most of the N required by plants (Schenk, 1996). The predominant form of plant available N is NO_3^-. Due to the negative charge of NO_3^- and NO_2^-, they are repelled by cation exchange sites and consequently not bound to soil colloids (McLaren and Cameron, 1990). Nitrate and NO_2^- exist entirely as ions in soil solution, while most of the NH_4^+ exists in exchangeable and clay fixed forms and very little is in soil solution (Keeney and Gregg, 1982).

Under natural conditions, N concentrations in soil solution vary in the range of a few to a few tens of ppm because of immediate plant and microbial demand. Thus, only a few kilograms of soluble N/ha may be available at any one time. In fertile systems available-N concentrations rarely exceed 100 kg N/ha (Young and Aldag, 1982; McLaren and Cameron, 1990; Schenk, 1996).

2.3.3.2 Mineral fixed ammonium

Mineral fixed ammonium is non exchangeable and is held within the lattice structures of silicate minerals. This entrapped NH_4^+, like potassium, fills interstitial lattice voids formed by hexagonal oxygen rings, and it serves to neutralise negative charges arising from isomorphous substitution. It resists removal by neutral salt solutions which are typically used for extracting exchangeable ions, and is therefore considered to be unavailable to plants and micro-organisms (Young and Aldag, 1982).

Fixed NH_4^+ is present in far greater quantities than exchangeable ammonium and in most agricultural soils represents 2-10% of the total N in the top 15 cm (Schenk, 1996; Young and Aldag, 1982).

2.3.3.3 Soil nitrogen gases

As in the above-ground atmosphere, N_2 is by far the dominant gas species within aerated undisturbed soil, representing >78% of the total gases in soils where physical barriers do not inhibit diffusion (Young and Aldag, 1982). The other two N gases found in the soil atmosphere are N_2O and NH_3 (Keeney and Gregg, 1982). Other gases such as NO and NO_2 have been detected in some emissions from field soils, but have not been found in the soil atmosphere (Linsay, 1979).

2.3.4 Organic forms of soil nitrogen

Over 84% of the N in the surface layer of most soils is organically combined (Stevenson, 1982b; Schnitzer, 2000). This fraction is often ignored from an agricultural viewpoint as this pool of N is not readily available for plant uptake. Organic matter however, plays a major role in agricultural production. It helps to provide good soil structure, is a source of energy for micro-organisms and is the source of the mineralisable N pool.

The organically combined N can be classified into three major groups, identified by soil analysis. These are amino acids, amino sugars and the hydrolysable unknown (HUN) fraction. The HUN fraction is made up of a wide array of compounds all of which generally occur in very small amounts. These compounds include nucleic acids and their derivatives, chlorophyll and chlorophyll degradation products, phospholipids, several amines, and vitamins (Stevenson, 1982b; Schnitzer, 2000).

2.3.4.1 Amino Acids

Kai *et al.* (1973) found that most of the amino acids in soil are in the cell walls of micro-organisms. Glycine, alanine, aspartic acid, and glutamic acid are often the dominant amino acids in these cell walls. Thus, most of the amino acid material that accumulates in soil is derived from peptides, mucopeptides and techoic acids of microbial cells (Stevenson, 1994). Amino acids have been found to account for 13-52% of total soil N in the surface layer (Stevenson, 1982b).

2.3.4.2 Amino Sugars

Amino sugars occur as structural components of a broad group of substances, the mucopolysaccharides, and they have been found in combination with mucopeptides and mucoproteins, as well as with smaller molecules, such as antibiotics. In soil, some of the amino sugar material exists as an alkali-insoluble polysaccharide referred to as chitin. This substance comprises the cell walls, structural membranes and skeletal components of fungal mycelia, where it plays a structural role analogous to the cellulose of higher plants (Stevenson, 1982b).

Amino sugars play the dual role in soil of serving as a source of N for plant growth and promoting good soil structure (Stevenson, 1994). Geoghegan and Brian (1946) and Haworth *et al.* (1946) found that nitrogenous polysaccharides have the ability to bind soil particles into aggregates of high stability.

Amino sugars make up 0.8-14% of the total soil N in the surface layer (Stevenson, 1982b; Stevenson, 1994).

2.4 NITROGEN TRANSFORMATIONS IN SOIL: THE NITROGEN CYCLE

The N cycle is the most complex and dynamic nutrient cycle within the soil system, with many transformations and many factors which affect these transformations. Although the organic N pool is the main reservoir of N in soils, it is primarily the plant available N forms that are of concern in defining the N status of soils. Due to the dynamic nature of this system it is not possible to simply measure the amount of immediately plant available N in the soil, as the N system is in a constant state of flux, with N being added and removed from this pool. It is important then that all of the N pools and transformations between them are considered when trying to estimate the amount of plant available nitrogen.

Human activity has greatly perturbed the natural N cycle through increased fixation of N by legumes, by energy input and fertiliser production, and by the mobilisation of N from long term storage pools (Goulding *et al.,* 1998). Figure 2.1 gives a diagrammatic representation of the various N pools in a managed soil plant system and the different pathways between each of these pools. In this section these pathways will be examined.

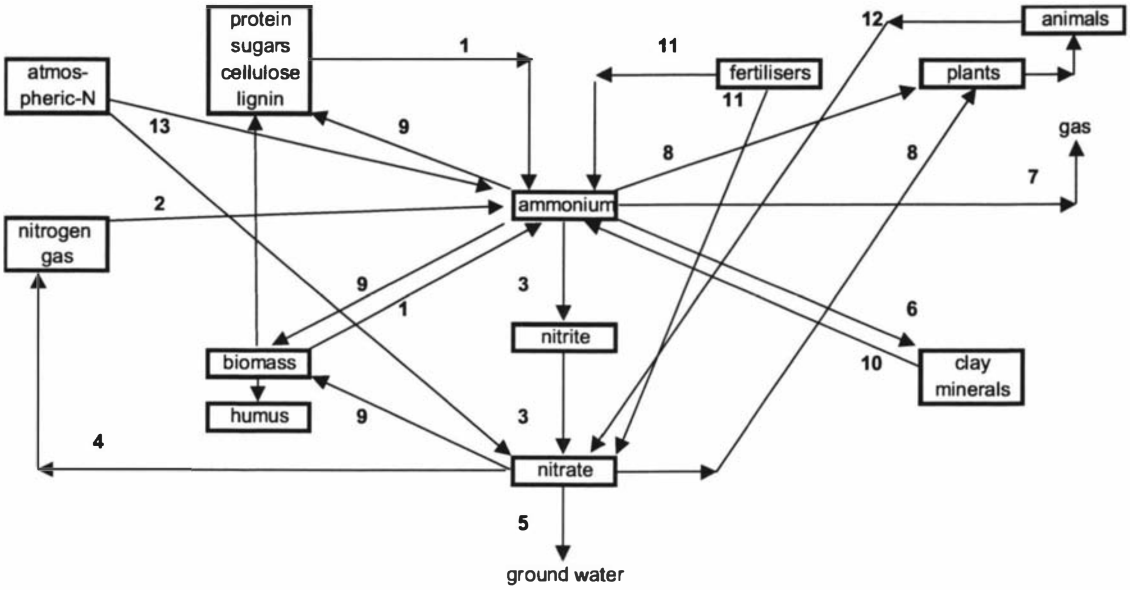


Figure 2.1 The various components of the N cycle and the pathways between each of the pools. 1. Mineralisation. 2. Biological fixation. 3. Nitrification. 4. Denitrification. 5. Leaching. 6. Fixation. 7. Volatilisation. 8. Plant uptake. 9. Immobilisation. 10. Mobilisation. 11. Fertilisation. 12. Animal excreta. 13. Precipitation.

2.4.1 Mineralisation and Immobilisation

In this section the ecological functions of mineralisation and immobilisation will be considered together. Both are biochemical in nature, and both are part of the activities of the organisms making up the heterotrophic biomass. The two processes work in opposite directions, building up and breaking down organic matter. The difference between the two will be a net effect, net mineralisation, or net immobilisation (Jansson and Persson, 1982; Janssen, 1996).

Nitrogen mineralisation is defined as "*The transformation of N from the organic state into the inorganic forms of* NH_4^+ *or* NH_3*. The process is performed by heterotrophic soil organisms that utilise nitrogenous organic substances as an energy source.*" N immobilisation is defined as "*The transformation of inorganic N compounds (*NH_4^+*,* NH_3*,* NO_2^-*,* NO_3^-*) into the organic state. Soil organisms assimilate inorganic N compounds and transform them into organic N constituents of their cells and tissues, the soil biomass.*" (Jansson and Persson, 1982). Plant uptake and assimilation of inorganic N compounds is a variant of immobilisation, as is N_2 fixation by autotrophic and heterotrophic soil organisms. These processes however, are usually excluded from the definition of immobilisation (Jansson and Persson, 1982).

The supply of N to plants is one of the most important factors governing crop production. With the exception of fertilisation, mineralisation and immobilisation are two of the most important processes which govern the amount of N that is available for plant uptake. It is therefore important that these processes are well understood in order to make an approximation of N transfers, and plant available N within the complete N cycle. The major factors affecting these processes within the soil system include:

2.4.1.1 The Carbon : Nitrogen ratio

The carbon:nitrogen (C:N) ratio is an important factor in determining whether net mineralisation or immobilisation occurs. Soil micro-organisms gain their energy from the breakdown of organic compounds and require a mixture of nitrogenous and non-nitrogenous decomposable substances in their "diet". If the organic materials that they are sourcing their energy from are N-free organic compounds, such as carbohydrates and lipids, then the microbes will source their N from the soil inorganic N pool and consequently net immobilisation will occur. If the situation is reversed and nitrogenous organic matter (proteins) is the source of energy, then net mineralisation will occur. The C:N ratio is a measure of whether the micro-organisms' "diet" is more rich in nitrogenous or non-nitrogenous compounds and whether net mineralisation or immobilisation occurs (Kai *et al.,* 1969; Jansson and Persson, 1982; Janssen, 1996; Jarvis *et al.,* 1996).

Mineral soils have an average C:N ratio of around 10 whilst organic soils have an average of around 30 (Stevenson, 1982a). In work carried out by Kai *et al.* (1969), where mineralisation and immobilisation were measured on two soils with C:N ratios of 8 and 32 it was found that the immobilisation rate in the soil with a C:N ratio of 32 was twice that of the soil with a C:N ratio of 8, over a period of 12 weeks. Hence net immobilisation occurred in the soil with a C:N ratio of 32, whilst net mineralisation occurred in the soil with a C:N ratio of 8. Similar results were found by Bartholomew (1965) and Janssen (1996), where net immobilisation occurred at higher C:N ratios and net mineralisation at lower ratios.

2.4.1.2 Temperature

Soil temperature can have a profound effect in determining whether net mineralisation or immobilisation occurs. The immobilisation and mineralisation processes are microbially driven which means that temperatures of greatest interest are in the 0-35°C range (Stanford *et al.,* 1973). Mineralisation practically ceases near freezing point, and at temperatures above 35°C ammonification (conversion of organic matter to ammonium) continues but nitrification slows and essentially ceases at 45°C (Harmsen and Kolenbrander, 1965). The rate limiting step in the mineralisation of organic N is ammonification, and in the 0-35°C range almost complete conversion of NH_4^+ to NO_3^- occurs in aerated soils (Stanford *et al.,* 1973; Jarvis *et al.,* 1996).

Kai *et al.* (1969), Campbell and Biederbeck (1972), Stanford *et al.* (1973), Ross and Bridger (1977), Carran (1979), Ledgard *et al.* (1989) and Clough *et al.* (1998) all found that mineralisation increases with increasing soil temperatures whilst net immobilisation increases as the temperature approaches zero. Added fertiliser N is therefore more likely to be immobilised when soil temperatures are lower (Ledgard *et al.,* 1989).

An exception to this occurs with the addition of fertiliser N at high temperatures. In this case the microbial biomass has an initial high uptake of the inorganic N, creating net immobilisation, which after 1-3 weeks changes to net mineralisation as the microbes revert back to breaking down the organic matter (Kai *et al.,* 1969; Campbell and Biederbeck 1972).

Chandra (1962) and Campbell and Biederbeck (1972) found that more mineralisation occurred when temperatures were shifted from optimal to sub-optimal than vice versa. The reason for this was thought to be that at optimum temperatures, production of microbial biomass was high but with the onset of sudden unfavourable temperatures there was initially a large die off of soil micro-organisms. This then provided a considerable amount of readily-available N substrate that was later mineralised and nitrified as the remaining organisms adapted to the new temperature regime. This has particular relevance to frosts and hail storms which can suddenly decrease the soil temperature.

2.4.1.3 Moisture

Moisture has a direct effect on N immobilisation and mineralisation. Mineralisation increases as the moisture level of the soil increases. The microbial biomass, like all other living organisms, require water to carry out cell functions. Therefore, when moisture becomes limiting the population of micro-organisms available to break down organic matter is reduced, thus reducing mineralisation (Miller and Johnson, 1964; Reichman *et al.,* 1966; Kai *et al.,* 1969; Campbell and Biederbeck, 1972; Ross and Bridger, 1977; Bottener, 1985; Jedidi *et al.,* 1996; Jarvis, 2000). It was reported that the optimum moisture is equivalent to that held by soil between 0.1 and 0.5 atm tension (Miller and Johnson, 1964; Reichman *et al.,* 1966).

Bottener (1985) and Jedidi *et al.* (1996) reported that the wetting and drying cycle of the soil has a major effect on mineralisation and immobilisation as well. They found that mineralisation increases in a soil which goes through frequent wetting and drying phases while immobilisation decreases. This has particular relevance to hill country, with northerly faces generally going through more dramatic wetting and drying phases than southerly faces. Mineralisation is therefore, likely to be higher on northerly faces than southerly faces due to higher soil temperatures and more frequent wetting and drying phases.

2.4.1.4 pH

The pH of soils has been shown to have an effect on the rate of N mineralisation in soils, with mineralisation increasing as the soil pH increases (Wheeler *et al.,* 1997). The pH of soil also has an effect on nitrification, and therefore determines whether the N mineralised remains in the soil as NH_4^+ or NO_3^-. An increase in pH favours nitrification which means that there is more NO_3^- in neutral soils than acidic soils (Jansson and Persson, 1982; Sapek, 1996). This implies that, although more N will be mineralised at a higher pH, there is also more chance of it being lost from the system by leaching and denitrification (refer to later sections).

2.4.1.5 Other factors

Although the factors listed above are the major ones affecting the rates of immobilisation and mineralisation in natural soil systems, there are also other factors that can have varying effects on these processes. Physical conditions such as water logging and compaction of the soil may affect aeration and establish more anaerobic conditions. This generally hampers microbial activity, especially nitrification which results in NH_4^+ or NH_3 accumulation, and also causes NO_3^- losses by denitrification, all of which may have an influence on whether net mineralisation or immobilisation occurs (Jansson and Persson, 1982; Jarvis 2000).

As mentioned in the section on temperature above, the addition of fertiliser N can also have an influence on mineralisation and immobilisation with an initial immobilisation of added N, which then changes to mineralisation after 1-3 weeks (Kai *et al.,* 1969; Campbell and Biederbeck, 1972).

2.4.2 Nitrification

Nitrification is a two-stage process involving the oxidation of NH_4^+ to NO_2^- and the subsequent further oxidation to NO_3^-. The reactions are strictly biological in nature and are carried out by autotrophic nitrifying bacteria (Schmidt, 1982). The nitrification process is not vitally relevant to plant growth as plants are also able to utilise NH_4^+ for growth. The nitrification process however, can influence the overall N cycle by determining how much NO_3^- is available for loss from the system via denitrification and leaching. It is therefore, relevant to investigate the factors which affect nitrification.

The main factors which limit nitrification are substrate NH_4^+, O_2, pH, and temperature (Focht and Verstraete, 1977; Hatch *et al.,* 1998; Jarvis, 2000). Substrate NH_4^+ has a direct effect, as it is the initial compound that is being oxidised. The other factors however, have varying effects.

Cold and wet soils are effectively inactive with respect to nitrification. Such limitations prevail until the soil warms to 4 or 5°C (Anderson and Boswell, 1964). Nitrification has been reported as occurring between temperatures of 4-60°C. The optimum temperature for nitrification appears to vary greatly depending on the type of soil with maximum nitrification rates occurring between 20-40°C (Mahendrappa *et al.,* 1966; Keeney and Bremner, 1967; Myers, 1975; Hatch *et al.,* 1998).

The O_2 required for nitrification is provided by the liquid phase of the soil system. This means that the amount and composition of the soil water can have an effect on nitrification by depleting O_2. Depletion of oxygen in the soil water is favoured by (i) high soil moisture content, which fills soil pores and restricts recharge of O_2 from the gaseous phase; (ii) high soil temperatures, which reduce the solubility of O_2 and increase O_2 demand by heterotrophic micro-organisms; (iii) oxidisable organic matter, which also increases heterotrophic O_2 demand. In organic soils with high microbial activity, nitrification is favoured by low temperatures as a result of decreased demand for NH_4^+ by heterotrophs and increased solubility of O_2 (Schmidt, 1982).

Nitrification proceeds at soil pH's far below limits observed by nitrifying bacteria in a pure culture in the laboratory. There has been no explanation found to resolve the anomaly (Schmidt, 1982). Most observations indicate that in the laboratory nitrification occurs in the pH range 7-8, whilst in soils nitrification occurs down to pH 4 (Weber and Gainey, 1962; Morrill and Dawson, 1967; Chase *et al.,* 1968; Sarathchandra, 1978; Keeney and Gregg, 1982).

2.4.3 Biological N fixation

Biological fixation of N_2 is one of the most important processes in agriculture, providing agricultural systems with a "free" source of nitrogen. The process is a unique property possessed by only a few genera of prokaryotic organisms that contain the genetic information to synthesise the enzyme nitrogenase. Nitrogenase catalyses the conversion of inert N_2 gas to NH_3 under mild temperatures and normal atmospheric conditions (Havelka *et al.,* 1982; McLaren and Cameron, 1990).

Two systems of biological N fixation operate: (i) fixation by free living micro-organisms, and (ii) fixation by micro-organisms which live in symbiosis with higher plants. The most well known and agriculturally important relationship is the root nodule forming symbiosis between *Rhizobium* species and some legumes. Bacteria of the genus *Rhizobium* invade the roots of host plants (mainly legumes) and form a root nodule within which they live and fix N_2. The plant provides the bacteria with carbohydrates for energy and the *Rhizobium* provides the plant with NH_3 (Havelka *et al.,* 1982; McLaren and Cameron, 1990). Most of the N that is fixed by the *Rhizobium* is however, not immediately available to associated grass species, as 90% of the NH_3 is utilised by the legume. Therefore the N fixed enters the soil-plant system either through the death and subsequent decay (mineralisation) of the legume plant material or through animal uptake and deposition (Ball, 1977; Carran, 1979; McLaren and Cameron, 1990; Ledgard *et al.,* 1996; Wheeler *et al.,* 1997).

Some free living N_2-fixing micro-organisms exist that are not directly associated with higher plants. Blue-green algae are one of the major groups of autotrophs capable of fixing N_2 in a number of different environments. There are also a number of bacteria in soil, such as *Azobacter,* that fix N at varying rates and thrive in various different conditions. As with legumes, the bacteria must die and decompose before the N fixed can become available to other plants (Cowling and Lockyer, 1965; Grant and Lambert, 1979; Havelka *et al.,* 1982; McLaren and Cameron, 1990).

In dry hill country farming, the predominant form of N_2 fixation is by clovers. As mentioned earlier in Section 2.1.2.6 in dry hill country farming, the predominant clover on warm hill slopes is subterranean clover. However, white clover is present on flatter and cooler sites. In general, even with adequate superphosphate fertiliser addition the clover content on hill country soils is low, with clover contributing between 1-11% of annual dry matter production (Suckling, 1975; Grant and Lambert, 1979). Therefore, the contribution to soil N from atmospheric fixation in dry hill country is low.

There have been many investigations of N fixation rates in pastoral soils. All of these have shown that rates vary dramatically. At the top of the range, estimates of 500-700 kg N/ha/yr of fixed N on flat-land sites with low initial soil N concentrations were reported by Allison (1955) and Sears *et al.* (1965). However, in hill country, values are much lower and range from 13 kg N/ha/yr for undeveloped pastures (Grant and Lambert, 1979) to 224 kg N/ha/yr for well developed pastures (Ball, 1977; Lambert, 1987; Ledgard *et al.,* 1987; Ledgard *et al.,* 1996). Fixation by non-symbiotic organisms was found to be about 16-20 kg N/ha/yr (Grant and Lambert, 1979).

The two primary factors that affect N_2 fixation are legume growth and inorganic N concentrations in the soil. Fixation is proportional to clover growth and therefore the more clover grown, the more N_2 fixed. Inorganic N in soil affects this relationship as it firstly encourages growth from competing grasses, which subsequently limit clover growth, and it also directly decreases fixation rates as the clover substitutes soil inorganic N for N_2 fixation (Ball, 1969; Ball, 1978; Crush *et al.,*1982; Ledgard *et al.,* 1982; Boller and Nosberger, 1987; Ledgard *et al.,* 1987; Mallarino and Wedin, 1990; Ledgard *et al.,* 1996).

Another factor which also has an effect, is the species of legume. Of the common legumes found in hill country, white clover fixes the most N_2 followed by subterranean clover, suckling clover, then lotus. There is also variation in the time of the year in which they each prevail. White clover prevails in summer-autumn, subterraneum clover in spring, while lotus prevails in the winter-spring (Ledgard *et al.,* 1987).

Nitrogen fixation can also be reduced by molybdenum deficiency (Havelka *et al.,* 1982; McLaren and Cameron 1990).

Legume growth and soil inorganic N concentrations are the two primary factors affecting N_2 fixation. However, there are a number of other components within the soil system that have an effect on these two factors. Legume growth and associated microbial activity and persistence is affected by extremes of temperature, moisture, light, pH, and nutrient status (Havelka *et al.,* 1982; Ledgard *et al.,* 1996). Soil inorganic N concentrations are affected by fertiliser additions, animal excreta, mineralisation rates and plant uptake (Ledgard *et al.,* 1987; Ledgard *et al.,* 1996).

Therefore, legume growth is influenced by a number of factors, all of which lead to fluctuations in N_2 fixation rates between seasons, climates and management practices.

2.4.4 Denitrification

Denitrification is the reduction of nitrate or nitrite to a gaseous form of N either as molecular N_2 or as an oxide of N. The process can occur through two mechanisms, the most important being biological denitrification and the other chemical denitrification (Firestone, 1982; McLaren and Cameron, 1990; Williams *et al.,* 1998).

Biological denitrification occurs in poorly drained soils, or in any situation where anaerobic conditions exist. In these situations facultative anaerobic bacteria can use nitrate as an electron acceptor, in place of oxygen, during metabolic reactions (McLaren and Cameron, 1990). The capacity to denitrify has been reported in 23 genera of bacteria (denitrifiers), of which 22 are aerobic organisms capable of anaerobic growth in the presence of the N oxides (Firestone, 1982). The generally accepted path of biological denitrification is displayed in Equation (2.1).

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \tag{2.1}$$

The last three steps of the denitrification process produce gases which are lost from the soil-pasture system. In humid tropical regions where soils can be waterlogged for large parts of the year, these losses can be substantial. Studies investigating denitrification under varying conditions have produced denitrification rates of 0-233 kg N/ha/yr (Ryden and Lund, 1980; Jordan, 1989; Aulakh *et al.*, 1992; Ruz-Jerez *et al.*, 1994; Groffman and Turner, 1995; Ledgard *et al.*, 1997; Luo *et al.*, 2000). Possible losses of added N can range from 0-70% of added fertiliser N (Firestone, 1982; Jarvis, 2000).

Losses can therefore be high, but in the case of dry hill country farms, the losses are likely to be lower and in the range of those reported by Ruz-Jerez *et al.* (1994) and Luo *et al.* (2000), of 3.4- 4.5 kg N/ha/yr. This is largely due to the conditions favouring denitrification not being present in dry hill country. The major factors that have an effect on denitrification are temperature, moisture, nitrate availability, C-substrate availability, and pH (Firestone, 1982; McLaren and Cameron, 1990; Luo *et al.*, 1994; Jarvis, 2000; Luo *et al.*, 2000). Of these, moisture and nitrate availability are likely to be limiting in dry hill soils.

Denitrification in dry hill soils in New Zealand is therefore, not likely to be a major problem. At times of the year when there is sufficient soil moisture to create anaerobic conditions, such as winter, there are the limitations of low temperature and nitrate levels. When there are no limitations imposed by temperature and nitrate concentrations, such as in summer, there are likely to be moisture limitations. The only exceptions where denitrification may be a problem are in the swampy margins of perennial and ephemeral streams (Ruz-Jerez *et al.*, 1994; Luo *et al.*, 2000).

2.4.5 *Fixation and mobilisation of ammonium*

The fixation and mobilisation of NH_4^+ in soil is largely an equilibrium process, involving exchangeable NH_4^+. Soil colloids are generally negatively charged, which means that the NH_4^+ is bound due to its positive charge and is able to be replaced by other cations with stronger binding powers. Ammonium is also able to bond to nonexchangeable sites, within the crystal lattice of aluminium and silicate clay minerals. This ammonium is non-exchangeable and is strongly held (Nommik and Vahtras, 1982). There are many factors which affect the fixation and mobilisation of NH_4^+, however, it is not viewed as an important issue in this study, and consequently, will not be covered in detail in this review.

2.4.6 *Volatilisation*

Ammonia volatilisation can be responsible for large losses of N from applied urea and ammonium fertilisers, and from urine patches. Volatilisation is the loss of NH_3 gas to the atmosphere, which may occur whenever NH_4^+ is converted to NH_3 at the soil surface (Nelson, 1982; Selvarajah *et al.*, 1989; Roelcke *et al.*, 1996; Pain *et al.*, 1998). If conditions are favourable, losses of N via volatilisation can be large. Work carried out by Selvarajah *et al.* (1994) on six different New Zealand soils found volatilisation losses of added fertiliser N ranging from 8.5- 53%. Similar losses have been found by Ernst and Massey (1960), Ferguson *et al.* (1984) and Roelcke *et al.* (1996). Variations in N loss via volatilisation can be attributed to a number of factors.

One of the major factors affecting volatilisation rates is soil pH. Many studies have shown that volatilisation losses are higher in soils with high soil pH (Ernst and Massey, 1960; Watkins *et al.*, 1972; Selvarajah *et al.*, 1989; Roelcke *et al.*, 1996). If urea fertiliser is being used, the rate of fertiliser can have an effect on pH, as when urea is hydrolysed to NH_4^+ there is an increase in pH. If a heavier rate of urea is applied, the pH increase is greater and therefore the loss via volatilisation is increased (Nelson, 1982).

Ferguson *et al.* (1984), Selvarajah *et al.* (1989) and Roelcke *et al.* (1996) all showed that the hydrogen ion (H^+) buffering capacity also has an effect on NH_3 loss through volatilisation. Losses were less on soils with higher buffering capacities. This is thought to be largely due to a reduced increase in pH when urea fertilisers are applied to the surface.

As with many of the other N transformation processes in soil, the rate of volatilisation is affected by temperature. The volatilisation rate increases as temperatures increase up to around 45°C (Watkins *et al.*, 1972; Prasad, 1976; Nelson, 1982).

Volatilisation rates are minimal when the soil is too dry for urea to dissolve. No correlation was found once soil moisture levels were above that required to dissolve urea (Martin and Chapman, 1951; Prasad, 1976). However, volatilisation is a surface effect and rainfall can decrease volatilisation by washing the urea or ammonium into the soil. Therefore, there is an indirect effect of moisture on volatilisation through rainfall (Selvarajah *et al.*, 1989).

Many workers, such as Terry *et al.* (1978), have shown that much more NH_3 is volatilised from surface-applied fertilisers than from fertilisers that are incorporated into the soil. This however, does not have a lot of relevance to hill country soils, as surface topdressing is often the only form of application possible due to the terrain.

As the aeration rate or wind flow increases across the soil surface, the rate of NH_3 loss also increases. This is due to the lower partial pressure of NH_3 in the atmosphere adjacent to the soil, thus permitting rapid diffusion of NH_3 from the soil in response to a large partial pressure gradient (Terry *et al.*, 1978; Roelcke *et al.*, 1996).

2.4.7 Leaching

Although the vast majority of soil N is relatively immobile, NO_3^- because of its negative charge, is repelled by cation exchange sites and is therefore readily leached when water drains through the soil (McLaren and Cameron, 1990).

Leaching losses of NO_3^- can vary greatly between regions and land use. The three main factors that affect leaching losses are, NO_3^- concentration, rainfall duration and intensity, and soil permeability. Leaching losses are increased as NO_3^- concentrations in the soil increase from fertiliser addition, or through build up via mineralisation. In New Zealand the major factor is the concentration of N in urine patches.

The permeability and amount of macropores in a soil also have a major effect. The faster the flow of water through the soil, the faster the rate of NO_3^- leaching, provided there is available NO_3^-. Therefore, sandy soils lose more NO_3^- than less permeable, clay soils. Rainfall has a major effect as it also determines the amount of water that moves through the soil profile. Areas that receive more rainfall, are more likely to have higher rates of leaching (Cameron *et al.,* 1989; McLaren and Cameron, 1990; Francis *et al.,* 1994; Sakadevan *et al.,* 1994; Addiscott, 1996; Hatch *et al.,* 1998; Jarvis, 2000). The intensity of rainfall however, is also important. Summer dry hill country may have low annual rainfall, but heavy rainfall events in summer are common. Therefore, in these periods leaching losses could be high due to a large amount of drainage through soil cracks or macropores.

As mentioned above there are a number of factors which affect the rate of NO_3^- leaching. There is therefore, a wide variation in the amount of NO_3^- leached between soil types and land uses. There have been reports of NO_3^- leaching of up to 200 kg NO_3^-N/ha/yr within New Zealand (McLaren and Cameron, 1990). However, within dry hill country, losses are likely to be much less. Sakadevan *et al.* (1994) measured rates between 1.3-3.7 kg N/ha/yr on hill country grazed by sheep. Williams and Haynes (1994) measured losses of 37 kg N/ha/yr on cattle-grazed pastures, due to cattle urine patches being much larger than those from sheep. Losses are likely to be less in dry hill country as there is much less drainage, and NO_3^- levels in the soil are also likely to be much lower than in fertile lowland soils. Losses could be high however, from stock camps during periods of high level rainfall, as described earlier.

2.4.8 Other inputs and losses

Other inputs and losses to the N cycle are fertilisation, animal excreta, precipitation and plant uptake. In the case of fertilisation and animal excreta return, the amounts of N which are added to the system can vary greatly due to the intensity of management practices and the type of stock farmed.

Additions of N to the system via precipitation are likely to be low, (1-10 kg/ha/yr, Stevenson, 1982a) and therefore only deserve a small mention, so as to note its occurrence.

Plant uptake of N will be discussed later in reference to factors affecting plant growth.

2.4.9 Conclusion

The breakdown of the N cycle above, shows how complex and diverse the system is. There are many different factors that affect each stage of the cycle and consequently the size of each of the N pools. The review has tried to give an insight into these various factors and provide an idea of the possible losses and inputs of N in the soil-plant system highlighting the seasonal and environmental effects.

2.5 PASTURE GROWTH AND NITROGEN RESPONSE

There are many factors that affect pasture growth, ranging from climatic and nutrient influences to the type of species. All of these play a role in either promoting or limiting pasture growth, and the degree to which they influence pasture growth can depend on what other factors are also limiting. One of the major factors that affects pasture growth is the supply of nitrogen. As this study is primarily concerned with the potential for N fertilisers in dry hill country, factors affecting pasture growth will be discussed in conjunction with N fertiliser response.

2.5.1 Factors affecting pasture growth and N response

Apart from fertilisation, the rate of supply of nutrients from soil to pastures is affected by many climatic factors (as mentioned in the N cycle). These are discussed below.

2.5.1.1 Temperature

Pasture growth is affected by air temperature and soil temperature. However, results obtained by Brougham (1959) and Baars and Waller (1979) show that pasture growth is more highly correlated with the soil temperature at 10 cm depth than air temperature. Due to differences in aspects and slopes the soil temperature in hill country pastures is likely to vary greatly across the landscape and throughout the year.

In general, pasture growth increases as temperature increases, until a critical level is reached. In the case of clover the maximum is around 35°C (Brougham, 1959; Smith and Stephens, 1976; Baars and Waller, 1979; Lemaire and Salette, 1982; Chapman and Macfarlane, 1985; Ledgard *et al.,* 1989; Whitehead, 1995). The increased growth as temperature increases, can be due to two factors. The first is the increase in cellular reactions within the plant (morphogenic effect), and the second is the increase in mineralisation rates within the soil, which increases the plant available forms of nutrients such as N (Carran, 1979).

Pasture growth ceases when the soil temperature at 10 cm depth falls below 5-10°C. The variation in lower limits can be attributed to variations between species. Ryegrass growth ceases at 6°C, whilst clover growth ceases at 9°C (Chapman and Macfarlane, 1985; Whitehead, 1995).

Although temperature has a large effect on the rate of pasture growth, most of the research investigating N response in relation to temperature suggests that N response is independent of temperature (Denium, 1966; Scott, 1972; Luscombe, 1980; Lemaire and Salette, 1982; Ledgard *et al.,* 1989). This is largely because the size of the response depends on both the increase in daily growth rate and also the duration of this effect. In cold conditions the effect may be slower but last longer. Therefore, total response may not be affected but the rate of response may be.

However in contrast, Scott (1972) found that N response by pasture was higher when N fertiliser was applied in warmer conditions. This is likely to be due to lower net immobilisation of the added N at higher temperatures mentioned in Section 2.4.1.2 on the N cycle. Luscombe (1980) found that the only time temperature had an effect on N response was in the winter when pasture on warm, north-easterly faces responded better than colder south westerly faces. It was thought that this was due to the temperature on the cooler faces falling below the threshold for growth to occur. Another exception was found by Luscombe (1979) where N response was more efficient on cooler faces than on warmer faces. A possible explanation was that the pasture growth on the warmer faces was limited by moisture more than the cooler faces.

2.5.1.2 Soil moisture

Soil moisture is probably the most important factor governing pasture growth, as all cellular processes require water to function and water is required for the uptake of nutrients into the plant. Pasture also uses water for cooling to dissipate the heat generated from the absorption of solar radiation. Pasture growth can be limited when the topsoil is dry, as it restricts the movement of valuable nutrient ions, even though adequate water is available from lower depths (Garwood and Williams, 1967; Lemaire and Denoix, 1987).

Pasture will not grow if the available soil moisture goes below a point known as the permanent wilting point (PWP) (McLaren and Cameron, 1990). The PWP is the moisture tension at which pasture is no longer able to draw any more water from the soil. At moisture contents above the PWP pasture growth will be limited whenever the potential evapotranspiration rate exceeds the amount of available soil water (Kerr *et al.,* 1986; Rickard *et al.,* 1986). Factors affecting evapotranspiration and its relative importance to pasture growth will be discussed in the section on evapotranspiration.

A soil's ability to retain water is affected by the soil structure and relative percentages of clay, silt and sand. Generally, more porous sandy soils will retain less water than compact clay soils (McLaren and Cameron, 1990). As mentioned in the section on the N cycle, the soil moisture can also have an effect on processes such as denitrification, leaching and mineralisation. Therefore, the amount of plant available N can be affected, which can subsequently alter the growth rate of pasture.

The N response of pasture is little affected by moisture, except when moisture becomes limiting (Penman, 1962; Smika *et al.,* 1965; Whitehead, 1995). Penman (1962) found that pasture growth was checked at a soil moisture deficit of 25 mm when 19 kg N was applied, whilst it was not checked until a moisture deficit of 38 mm, when 38 kg N was applied. These findings were backed up by Smika *et al.* (1965) who found that the water use efficiency of pasture increased as N fertilisation rate increased, due to a larger and deeper rooting system in the fertilised pasture. It is therefore, likely that N fertiliser will increase the ability of pasture to keep growing when soil moisture becomes limiting.

2.5.1.3 Light

Light is an essential input for all plants as it is necessary for photosynthesis (Whitehead, 1995). Deinum (1966) showed that as light intensity increased so did pasture growth, with the highest growth rate being recorded at a light intensity level equivalent to that of a mid summer's day, and lowest during a dull winter day. The N response was also found to increase as light intensity increased, with the greatest nitrogen response being recorded during the mid summer-equivalent light intensity. Usually as sunlight intensity is increasing or decreasing, so is temperature, so its effect can be multi factorial (Lemaire and Salette, 1982; Whitehead, 1995).

2.5.1.4 Rate of defoliation

Pasture growth rate follows a sigmoidal curve in relation to leaf area. Pasture growth rate is low at low pasture covers, and then increases linearly as pasture cover increases, before slowing as pasture cover becomes too great and causes shading, and senescence and decay occur (Brougham, 1956).

Pasture grows fastest when the interval between defoliations is at least six weeks (MacLusky and Morris, 1964: Davies, 1988). Generally the less frequent the defoliations the faster the rate of growth, until a point is reached where the leaf reaches senescence and decays. The slower growth rate is largely due to less leaf area to receive energy for photosynthesis (Holliday and Wilman, 1965). However, Scott (1972) found that pasture growth was unaffected by the rate of defoliation, except in winter when more frequent defoliations increased pasture growth of a ryegrass-clover mixed sward. There was no apparent reasons found in this study for why more frequent defoliations increased pasture yield. In general, the response to fertiliser N is increased as the period between defoliations is increased (Whitehead, 1995).

The height at which a pasture sward is cut also has an effect on pasture growth rate. Brougham (1956) investigated growth rates when pasture was cut to 2.5, 7.5 and 12 cm and showed that the more intense the defoliation, the lower was the initial rate of regrowth and the longer the time taken to attain maximum growth rate. In general, in order to maximise herbage yield per year, it is best to combine severe defoliation with a long regrowth period or more lenient defoliation with a shorter period of regrowth (Robson *et al.,* 1989).

2.5.1.5 Nutrients

The yield of pasture is affected by the supply of nutrients ranging from major nutrients such as phosphorus (P), potassium (K), and sulphur (S), through to trace elements such as copper (Cu). The level at which these nutrients become limiting to pasture growth is dependent on a number of factors such as species and the potential growth rate due to physical factors. The faster the growth rate of pasture, the higher the demand for each nutrient. Although pasture growth is affected by the supply of a wide range of nutrients, the yield response of pasture to fertiliser N is normally only affected by the associated supply of P, K and S, and sometimes Mo and Co (Whitehead, 1995).

2.5.1.5.1 Phosphorus

As mentioned earlier P deficiency is widespread throughout hill country pastures (Chapman and Macfarlane, 1985). Pasture generally contains between 0.3-0.4 % P in dry matter, with 0.3 % being the critical level at which P is considered deficient (McLaren and Cameron, 1990). Each species of pasture can respond differently to P, with clover generally responding better than ryegrass (Chapman and Macfarlane, 1985). Mackay *et al.* (1990) and Roach *et al.* (1996) both found decreases in pasture production of between 29-35 % per year when 250 kg P/ha of superphosphate fertiliser was withheld from hill country pastures in New Zealand.

Studies in the U.K. by Gething (1963), Wolton *et al.,* (1968) and Kirkham and Wilkins (1994) have all shown that N response is increased with increased rates of P fertility. It is surprising that given the obvious P deficiency in New Zealand pastures, there is little evidence that the size of the N response is affected greatly by P response. Ledgard and Saunders (1982) found no P x N interaction on a Bruntwood sandy loam, until a rate of 740 kg N/ha applied as urine was combined with 210 kg P/ha. This indicated the P requirement on that soil was limited only at very high N rates.

2.5.1.5.2 Potassium

Potassium can be a limiting nutrient for grass growth especially on sandy soils which have little capacity to retain K by cation exchange (Whitehead, 1995). Gillingham and During (1973) reported that K can be lost from hill country soils at rates of 22-38 kg K/ha/yr.

Several studies in the U.K. have shown that pasture response to N fertiliser is also dependent on K fertiliser. Reith *et al.* (1961) showed that the effect of K fertiliser on pasture response to N fertiliser increased as the rate of N fertiliser increased. The effect occurred up to the maximum N fertiliser rate of 390 kg N/ha/yr. The K fertiliser effect occurred only in the presence of N fertiliser and became more pronounced in the second and third years of the investigation, indicating that K was progressively depleted. Other overseas studies have also shown that N response is increased with K fertiliser application (Holmes and MacLusky, 1954; Castle and Holmes, 1960; Kirkham and Wilkins, 1994). However, a study by Ledgard and Saunders (1982), found that K had no effect on N response except when a high level of K fertiliser was used in conjunction with a high level of urine, which decreased the total pasture yield. This was thought to be due to high levels of K in the urine creating a toxicity. This highlights that there is little obvious effect of K on N response in New Zealand pastures.

2.5.1.5.3 Sulphur

Pasture generally responds to the application of fertiliser S with the greatest responses occurring on light textured soils (Syers *et al.,* 1987). Similar findings were found in other trials carried out in the U.K. where N response was increased by increased supplies of S (Stevens and Watson, 1986; Skinner, 1987; Murphy and O'Donnell, 1989). Faulalo (1997) however, found little response in a New Zealand hill country pasture to additions of fertiliser S, but it was reported that N response was increased with adequate supplies of S in the soil, indicating that S became limiting when increased potential pasture growth rates were achieved.

2.5.1.6 pH

Soil pH has little effect on the response of pasture to fertiliser N if it is above about 4.5, but the response is curtailed at lower pH values (Van Burg *et al.*, 1982).

2.5.1.7 Species

The evolution of grass species in differing environments, has meant that these species have developed differing requirements for N. Although N has been shown to be a major factor in governing pasture growth, with increasing supplies of N increasing production, there are some exceptions. *Calluna vulgaris* and *Nardus stricta* are known 'nitrophobes' and *Atriplex hastata* has been shown to grow well under conditions of N deficiency (Bradshaw *et al.*, 1964). Overseas there is therefore, variation between species in response to N.

However, in New Zealand in pure grass swards, species that are considered low fertility species have the ability to respond as well to fertiliser N as high fertility species such as ryegrass (Luscombe, 1980). In two studies by Luscombe (1979, 1980) investigating N response in hill country pastures, grasses such as browntop, sweet vernal and crested dogstail produced greater responses to N fertiliser up to rates of 160 kg N/ha than did ryegrass. Ball and Field (1982) made the observation that it is unusual that there is no difference in N response between most New Zealand species.

The response of pure grass swards to N fertiliser is likely to vary from grass-clover mixtures. It is generally well accepted that the addition of fertiliser N to a grass-clover mixture will reduce the amount of clover in the mixture (Frame and Boyd, 1987; Whitehead, 1995). Luscombe (1980) however, found that N fertiliser had no effect on the clover content in hill country pastures, as the initial clover content was already relatively low. The response of a pure grass sward up to a level of 300-400 kg N/ha/yr is likely to be larger than a grass-clover mixture, however, the total pasture production is likely to be higher in the grass-clover mixture (Cowling and Lockyer, 1965; Reid, 1983; Whitehead, 1995).

2.5.2 Dry Hill Country

In dry hill country, the major factors determining pasture growth rates are aspect, slope and season, as these three factors can lead to major differences in soil moisture and temperature, which affect the supply of nutrients and pasture growth.

A study by Radcliffe (1975), investigated the seasonality of pasture growth on drought prone country at Maraekakaho in the Hawkes Bay. Pasture growth averaged around 10 kg D.M./ha/day throughout the year, except for the period from early August till the end of November. Over this period, daily growth rates were significantly increased. The growth rate peaked at 47 kg D.M./ha/day in September, and the period from September to late October produced half of the annual 6740 kg D.M./ha production. The peak in growth rate over this period can be attributed to increases in temperature and light, leading to increased mineralisation rates, coupled with favourable soil moisture levels providing good growth conditions for pasture. From November through until the start of May, soil moisture was the major limiting factor. When soil moisture was adequate, pasture growth rates reached up to 25 kg D.M./ha/day, but when it was limited they were restricted to 5 kg D.M./ha/day. From May through to early August, temperature became the major factor limiting pasture growth. The decrease in temperature, reduced net mineralisation of N and limited the plants' metabolism. This study provides a general guide to the seasonality of pasture growth in flat dryland country, however, once aspect and slope are added, even more variation occurs.

The difference in growth rate and N response between aspects arises largely as a result of radiation differences which are due to changes in the path of the sun throughout the year. In the summer the sun is very high in the sky and therefore, all aspects receive similar amounts of sunlight. In the autumn, winter and spring periods the sun is much lower in the sky and consequently the northerly-facing aspects receive more sunlight than the southerly aspects (McAneney and Noble, 1976).

A study by Luscombe (1980) investigated N responses on north-easterly and south-westerly aspects throughout the year. North-easterly aspects produced more pasture through winter and mid to late spring than south-westerly aspects. Throughout the rest of the year there was no significant difference in the growth rates between aspects. The largest differences occurred in mid to late spring when the north-easterly aspects produced approximately 16 kg D.M./ha/day more than the south-westerly aspects.

Nitrogen response by pasture was highest throughout the spring period, with average responses of around 30 kg D.M./ha/day for both aspects when 160 kg N/ha/yr of fertiliser was applied. This suggested that N mineralisation over this period was a major limiting factor of growth over this period, with the climatic potential for N uptake exceeding the rate of N supply. This theory was supported by Carran (1979) and Ball and Field (1982).

Luscombe (1980) thought that the N response would have been reduced in late spring due to more N being mineralised, as a result of higher soil temperatures. However, the low legume content meant that there was insufficient organic N substrate available for mineralisation. Grant and Lambert (1979) reported this as a common problem in hill country with a low legume content.

The N response remained similar between aspects for most other times of the year, except for winter, when the south-westerly aspect was severely limited by temperature, and in early autumn when the north-westerly aspect was limited by moisture. In areas that are more affected by summer dryness southerly aspects are likely to produce more pasture and a greater N response than northerly aspects due to more severe water restrictions on the northerly aspects (Chapman and Macfarlane, 1985).

In contrast to the above findings, Lambert (1977) found in the absence of added fertiliser N, southerly aspects produced more grass than northerly aspects at all times of the year except for early summer. This may have been due to the northerly aspect experiencing much more wind than the southerly aspect, which may have hampered pasture growth. This shows that there is going to be some variation between regions and years as to how large the difference between aspects is.

The effect of slope is also likely to vary throughout the year. As a slope becomes steeper it is more likely that the soil will be shallower. This may reduce the amount of water and nutrients available for pasture growth (Luscombe, 1980). Ledgard *et al.* (1982) investigated the effect of slope on pasture growth over winter and spring. They found that increasing slope decreased pasture growth most in the months of September and October. It had a marginal effect in May and August, and had little to no effect in June and July. This appears to show that as the sun becomes lower in the sky over winter, differences in temperature and light between the steep and flat sites are equalled out, and at that time of the year the steep sites are less likely to be affected by moisture stress.

2.6 PASTURE GROWTH MODELING

There have been numerous studies carried out that investigate the potential to accurately model pasture production. The models range from being very basic in their format, using only one or two climatic variables such as maximum daily air temperature (Wallach and Gutman, 1976; Lile and George, 1993), to quite complex, using multiple climatic, soil and pasture variables (Baars, 1980; Thornley and Johnson, 1990; Woodward, 1999). All of the models have limitations, either in terms of accuracy, lack of applicability to specific regions, climates and landscapes, or the amount of information required as inputs to generate pasture growth data.

One approach to pasture growth modeling investigated by a number of authors, which requires few inputs and has the potential to be applied to varying climates, is to relate pasture growth to evapotranspiration (E_t). The discussion below examines the development of this approach.

2.6.1 Evapotranspiration

Evapotranspiration is a term that was first coined by Thornthwaite (1948). The term refers to the loss of water from the soil via the combined means of transpiration from plants and evaporation from the soil surface. It is an important term in relation to pasture growth with a number of authors showing a close relationship between pasture growth and the rate of E_t (McAneney and Judd, 1983; Hanks, 1992; Moir *et al.*, 2000).

Within New Zealand there are three methods by which E_t has been estimated. These are the Penman (1948), Thornthwaite (1948) and Priestley and Taylor (1972) formulae. All of the formulae use a similar basic principle of trying to measure the amount of energy that is entering the soil-plant system to then estimate the amount of transpiration that is occurring on any given day from a sward of dense, short-cut grass that is freely supplied with water (Kutilek and Nielsen 1994). Penman (1948) and Thornthwaite (1948) simultaneously introduced the idea that weather and climate control evapotranspiration, and that plant differences are usually of minor importance.

Penman was an English agricultural physicist, and the formula that he proposed had a sound physical basis. Estimated E_t consisted of the sum of two terms. The first estimated the equilibrium evaporation rate using solar radiation, a constant called the psychrometric constant and a value relating the amount of water vapour air can hold at a given temperature. The second term includes wind speed and humidity (Marshall *et al.*, 1999). The formula has been shown to be accurate for well-watered pasture in New Zealand (Clothier *et al.*, 1982).

Thornthwaite was an American geographer and his formula has a weak physical basis, and relies on an empirical relationship between E_t and air temperature derived in the U.S.A. As it is generally accepted that solar radiation rather than air temperature drives E_t (Scotter *et al.*, 2000), and the relative air temperature and solar radiation levels in the U.S.A. are different to most other countries in the world, it is not surprising that the Thornthwaite formula is not that accurate outside of the U.S.A. and generally unreliable for estimates in New Zealand (Coulter, 1973a; Hanks, 1992).

The Priestley and Taylor (1972) formula (Eq. 2.2) is derived from the Penman (1948) formula. It however, uses less parameters to estimate E_t and has been shown to be just as accurate as the Penman (1948) equation (Clothier *et al.,* 1982). It is therefore the preferred means of estimating E_t. The equation can be written as

$$E_t = \frac{1.26sRn}{\rho wL(s+\gamma)} \qquad (2.2)$$

where s is the slope of the relationship between the saturated vapour density and temperature, γ is the psychrometric constant, Rn is the net radiation over the 24 hour period (MJ/m^2). ρw is the density of water (1000 kg/m^3), and L is the latent heat of vaporisation of water at ambient temperature (2.5 MJ/kg).

A number of studies have shown linear relationships between E_t and pasture production (Rickard and Fitzgerald, 1970; Wright and Baars, 1976; McAneney and Judd, 1983; Rickard *et al.,* 1986; Faulalo, 1997; Moir, 2000). Therefore, E_t may have potential in predicting pasture production, as it provides a means of summarising the major climatic variables affecting pasture growth (energy inputs and soil moisture) into a single factor.

Most current models used to predict the response to added fertilisers lack the ability to quantitatively predict pasture growth except in terms of relative yield (Moir, 2000). This restricts the applicability of the models in whole farm system modeling and economic analysis.

However, relating pasture production to E_t, may allow quantitative prediction of pasture production, taking into account the year-to-year and site-to-site climatic variability. This approach may open up the possibility of a new generation of prediction models that can quantitatively predict pasture yields under different levels of soil fertility by removing the effect of climatic variation.

2.7 CONCLUSIONS

The review of literature presented above, provides an overview of pasture production in dryland hill country, and the factors affecting it- in particular by N. The literature suggests that dryland hill country farming is a form of agriculture in which there are a vast range of variable factors that have a major influence on the type of farm practices that are employed. Unlike their lowland counterparts who farm in generally more favourable conditions, the choice of farming type for hill country farmers is severely restricted. In general, dryland hill country farms run mainly sheep, with some cattle on the less steep country. This is due to a number of factors including the terrain limiting cultivation, the high risk of drought enforcing flexible stocking rates, and the low soil fertility that reduces production and rules out more intensive farming practices. Therefore, dryland hill country farms are forced into farming dry stock that often provide low financial returns. This lack of options in terms of farming type, requires farm policies that make the most efficient use of expensive inputs such as fertiliser.

The varying topography and dry nature of the climate means that there are a number of microclimates produced on individual slopes and aspects. These cause pasture production to be limited at varying times throughout the year by either energy inputs or moisture. These limitations however, cannot be altered (unless irrigation is used) and it is therefore, a case of adopting farming practices that work around these limitations.

The most common limitation on dryland hill country outside of climate, is N. Nitrogen is a limitation which can be over come by either increasing clover growth or by the use of nitrogenous fertilisers. One of the major reasons that dryland hill country farms are so deficient in N however, is the lack of clovers. Therefore it is important that the severity of N limitation and the consequent potential for N fertilisers be identified.

The literature shows that the N cycle is a complex and “volatile” system. In the soil there are a number of pools of N and the sizes of these pools fluctuate constantly in response to a large number transformation processes. Due to most of the soil N existing in organic combination the most important process which occurs in soil and largely determines the amount of N that is available for pasture production is mineralisation. Mineralisation converts N from an organic form into an inorganic form which the pasture can utilise for growth. The mineralisation process is a biological conversion and is subsequently very dependent on a number of environmental factors. The most important is probably temperature. As the temperature increases so does the rate of mineralisation and vice versa.

The wide range of microclimates in dryland hill country, means that there is a large variation in soil temperature regimes throughout the year. Therefore, pasture on different sites in the landscape will experience varying degrees of N limitation depending on the relative effects of soil temperature on mineralisation and plant growth.

Although, pasture production is severely limited by N in dryland hill country, many studies have shown that there is great potential for overcoming these deficiencies by application of N fertiliser. The levels of response vary with rates of application, timing, and sites. However, in general, good responses were found by all studies.

Therefore, in the current farming environment, increased profits have opened the door for increased use of N fertilisers in dryland hill country. However, to optimise the increased inputs of N fertiliser, more precise methods need to be adopted which can account for the variation in N response between sites and seasons. Present models predict pasture yield in terms of relative yield, but quantitative yields are needed for accurate "decision support" fertiliser models. A new approach adopted by a number of authors which uses E_t to predict pasture yields appears to provide a method by which, more accurate quantitative predictions of pasture yield and fertiliser response can be measured for varying sites.

Therefore, dryland hill country farming provides a lot of challenges in terms of developing appropriate farming policies due to the large number and variability of constraints on production. One of the largest constraints – N supply, appears to have the potential for being easily overcome through the increased use of N fertilisers. However, due to variations in response between sites throughout the year, it needs to be ensured that application is cost effective and efficient. More accurate model's, such as those which predict pasture growth in relation to E_t will allow this to happen.

CHAPTER 3

THE WAIPAWA FERTILISER TRIAL

3.1 TRIAL LOCATION AND SET UP

In this study all of the research has been conducted on one trial site- the Waipawa fertiliser trial.

The trial was established to measure the effects of P and N fertilisers on pasture and animal production from dry hill country and to evaluate the relative profitability of using one or both of these fertilisers. It is a large scale, 48 hectare, trial located approximately 4 km west of Waipawa township in central Hawkes Bay, New Zealand, on dry steep hill country. The trial started in May 1995 and is operated by AgResearch with initial industry support funding from Ravensdown Fertiliser Cooperative Ltd and from Petrochem Ltd and latterly from Fert Research. Along with research into production agriculture, environmental studies are also conducted at the trial site investigating management effects on water quality and surface runoff.

The trial site has an annual rainfall of approximately 800 mm, being winter wet and summer dry (see Table 3.1). The soil type is Waipawa silt loam (Rocky Recent Soils). This averages about 60 cm in depth and overlies white argillite rock which is exposed on some ridges.

Table 3.1 Average monthly and yearly rainfall from 1994-1999 in mm.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
Av	90	61	53	84	56	77	112	52	35	46	64	43	789
Max	153	112	95	216	87	164	160	119	78	97	178	122	996
Min	71	12	5	27	22	39	76	14	8	21	19	3	463

Soil moisture levels are generally highest in July then decline in spring and summer before being recharged with autumn and winter rain. Soil on the south aspects is at a higher gravimetric moisture content than that on north aspects at all times. The difference ranges from about 5% in summer (i.e. 15 and 10% respectively) to about 20% in winter and early spring (i.e. 55 and 35%). It can be expected that there will be a dry period every year in the spring to early summer period which will limit pasture growth over what would otherwise be relatively high potential production.

The trial has four contrasting fertiliser treatments, applied separately to four farmlets. Each farmlet is 12 hectares in area, consisting of 12 one-hectare paddocks covering medium to steep slopes and both north- and south-facing aspects. Before the trial began an intensive soil survey was conducted over the trial area. This was to ensure that the trial was spread over a uniform, representative soil type defined as the Waipawa silt loam. Any areas that contained soils of a different type were left out of the trial area. Measurements of pasture species composition, topography and soil nutrient status were also made prior to the set up of the trial area. The data were used to allocate paddocks to treatments so that each was balanced in as many factors as possible. Paddocks within each treatment or farmlet are spread across the whole trial area rather than clumped in a quarter of the area. At the commencement of the trial therefore, each farmlet was very similar to the others.

A basal fertiliser of maxi-sulphur superphosphate plus molybdenum was applied over the whole area in September 1994 before the trial commenced. This raised the soil sulphur test levels to the 10-12 range where they have been maintained with appropriate applications of sulphur containing fertilisers. White clover and subterraneum clover seed was also applied at this time.

Two of the farmlets have an Olsen P test of 10 (original P status) and the other two have a test level of 28 (paddock averages). The high-P farmlets received an application of 500 kg/ha of triple super phosphate (20% P) before the commencement of the trial to raise the P levels to the desired level. One each of the 'Low P' and 'High P' farmlets receives N fertiliser in early to mid winter at a rate of 30 kg N/ha. The four farmlets can therefore be classified as 'Low P' (LP), 'High P' (HP), 'Low P plus N' (LP+N), and 'High P plus N' (HP+N).

The trial is stocked with an approximate 65:35 ratio of sheep (five year old Romneys) and cattle (18 month old Friesian/Angus). The stocking rate is set to fully utilise the expected pasture growth from each farmlet with ewes only in winter, with cattle added as needed to control pasture in spring. The LP farmlets are stocked at 7.1 su/ha, while the HP farmlets are stocked at 8.1 su/ha. This allows for a clearer expression of the effect of nitrogen application at each stocking rate. Each farmlet is self contained.

Replacement ewes go into each farmlet in autumn prior to mating and cattle are introduced in early spring. The stock policy is to manage all ewes so that their body weights are similar across all farmlets and for the cattle to buffer any shortage or to take up any surplus feed. Cattle are removed and sold when feed availability is insufficient to maintain or increase body weight without reducing sheep feed. Lambs are weaned in early summer.

Pasture and soil measurements are made in each of the farmlets from more than 100 identified sites, investigating pasture growth rates, botanical composition, and nitrogen and phosphorus fertilities on easy and steep slopes within north- and south-facing aspects throughout the year. Further information on the trial has been provided by Gillingham *et al.* (1998).

The Waipawa fertiliser trial therefore, provided an ideal location in which to conduct this trial investigating the major pasture growth limitations (with an emphasis on N) on dry steep hill country across a range of aspects, slopes and phosphate fertilities.

Plate 3.1 View of the typical dry hill country at Waipawa.

CHAPTER 4

PRE TRIAL SOIL TESTING

4.1 INTRODUCTION

The purpose of this study was to examine the constraints placed on pasture growth by N availability at this trial site on summer-dry hill country. As indicated in the previous section, two fertiliser treatments had been imposed on the grazing area. A large capital application of P fertiliser had elevated Olsen P levels on the high P sites and small annual applications of N fertiliser had been applied to the plus N sites. Although regular routine soil testing had been undertaken, there had been little detailed study of the underlying soil fertility of the site.

It was realised early on that resource and time constraints would limit the size of the field trial that could be undertaken in this PhD study and that not all of the large scale grazing trial would be required. A preliminary survey was therefore done across the whole grazing trial to enable atypical sites to be identified and excluded from the smaller-scale trial established for the study reported in this thesis.

In this survey it was decided to analyse for Total soil N and Total soil P because, although these parameters are not sensitive indicators of plant nutrient availability, they are representative of underlying processes of soil development and can identify fundamentally atypical sites, as well as reflecting the long term impacts of slope and aspect on soil formation.

Before large scale soil sampling was undertaken a smaller survey was conducted over a number of random sites throughout the trial investigating the change in total N and P with soil depth. Three soil depths 0-37.5mm, 37.5-75mm, and 75-150mm were chosen. The results indicated that there was no major difference between sites in N and P measurements below 75mm. It was therefore decided that soil samples would be collected and analysed from 0-37.5 mm and 37.5-75 mm soil depths.

4.2 MATERIALS AND METHODS

Samples were statistically analysed using a multi-factorial unbalanced analysis of variance.

4.2.1 Soil sampling

Under the current trial site operation there are 100 sites at which pasture and soil measurements are made. These sites are on a range of aspects (north, south and flat), slopes (easy and steep), and fertilities (high P, low P, and plus and minus N). There are therefore, 20 major treatments and five reps of each. The differing slopes and aspects are described as northerly easy (NE), northerly steep (NS), southerly easy (SE), southerly steep (SS) and flat (F). Soil samples were taken from all of these sites in October 1999. Soil cores were taken using a standard soil sampler to a depth of 75 mm. Six cores were taken from each site and the cores were separated into two depths of 0-37.5 mm and 37.5-75 mm, before the six cores were bulked together to give a single sample for each depth at each site.

4.2.2 Soil analysis

The soil samples were air dried and then finely ground in a ring grinder. A 0.1000g sample of the soil was placed in a Pyrex tube with 4ml of Kjeldahl digest mixture (McKenzie and Wallace, 1954) and heated to 350°C for four hours. The solution was then diluted to 50 ml using deionised water and mixed thoroughly in a vortex mixer. The samples were then analysed for nitrogen and phosphorus on a Technicon II autoanalyser.

4.3 RESULTS AND DISCUSSION

4.3.1 Total N

There was a large variation in total N values in the 0-37.5 mm depth, ranging from 3.62 to 5.90 mgN/g of soil for the HPNS and LPSE plus-N sites respectively (Table 4.1).

These values are lower than total N values recorded by Moir (2000) to a depth of 75 mm for an area of similar rainfall. Values recorded in that study ranged from 4.40 to 7.95 mgN/g of soil. Values are likely to be higher in that study due to samples being taken only from flat sites which have been shown to have higher soil N concentrations than slopes, as shown in this study.

Table 4.1 Total N concentrations (mgN/g) of soils in the 0-37.5 mm depth.

Treatment	**Control**	**Plus Nitrogen (30 kg N/ha)**
HPNE	4.50	5.06
LPNE	4.70	4.58
HPSE	5.18	5.50
LPSE	5.08	5.90
HPNS	3.72	3.62
LPNS	4.00	4.22
HPSS	4.74	4.88
LPSS	4.84	5.48
HPF	5.44	5.42
LPF	5.50	5.80

There were significant differences in the total N content of the soil in the 0-37.5 mm depth across the varying aspects and slopes (Table 4.2). The key contrasts were:

- Significantly higher total N levels on southerly sites compared to northerly aspects.
- Significantly higher total N levels on easy slopes in comparison to steep slopes.
- Significantly higher total N levels on flat sites in comparison to northerly and steep sites, yet similar total N levels between flat and easy sites.

Table 4.2 Statistical significance of total N and P concentrations in the 0-37.5 mm and 37.5-75 mm soil depths.

Contrast	**N 0-37.5 mm**	**N 37.5-75 mm**	**P 0-37.5 mm**	**P 37.5-75 mm**
Phosphorus	-	-	**	-
Nitrogen	-	-	-	-
P*N interaction	-	-	-	-
North vs. South	**	**	**	**
Easy vs. Steep	**	**	*	**
North vs. Flat	**	**	**	**
South vs. Flat	-	**	-	*
Easy vs. Flat	-	**	-	*
Steep vs. Flat	**	**	**	**
NE vs. NS	**	*	-	-
NE vs. SE	*	*	**	**
NE vs. SS	-	-	*	-
NE vs. F	**	**	**	**
NS vs. SE	**	**	**	**
NS vs. SS	**	*	*	-
NS vs. F	**	**	**	**
SE vs. SS	-	**	**	**
SE vs. F	-	-	-	-
SS vs. F	-	**	-	**
Depth	**	**	**	**

* = $P < 0.05$, ** = $P < 0.01$

Jenny (1961) expressed the concept that soil development is a result of the interaction of climate, relief and soil organisms acting on a parent material throughout time. Climate here refers to the annual contrasts of solar radiation, precipitation, evapotranspiration and their effects on soil temperature and water regimes. Relief includes landform elevation, slope profile, contour and aspect. The relative rate of soil development is a function of the energy available for the biological and chemical systems, and the efficiency with which soluble reactant products are leached from the soil landscape system (Yaalon 1960). The input of solar radiation, either directly to the soil or indirectly via biochemical pathways, stimulates evaporation, transpiration and ultimately determines the rate of chemical reactions (Jenny 1980; Birkeland 1984). Therefore, if available water was non-limiting, soil development should be faster on sunny aspects than on shady aspects (Tonkin 1985). However, in these soils water is not always non-limiting and it therefore, slows the development process by reducing biological activity, especially on sunny faces where the soil dries out faster and more frequently due to the higher solar radiation inputs.

The statistically significant differences in total N measurements (Table 4.2) between slopes and aspects, largely reflect differences in organic matter content resulting from a complex interaction of the soil forming factors described above.

The significantly higher levels of soil total N on southerly sites in comparison to northerly sites can largely be attributed to the higher level of energy inputs on the northerly sites. This higher input of energy operates in two ways. The first is the creation of higher soil temperatures, which increases the rate of breakdown of organic matter, and reduces the total soil N concentration. The second, is through lower soil moisture contents, which limit pasture production on NS sites and the subsequent input of organic material back into the soil profile.

The easy and flat slopes also have a significantly higher total N content than the steep slopes. There are two key explanations for the differences. The first is that soil moisture levels are likely to be lower on steep slopes due to shallower soils and less effective rewetting from rainfall due to more runoff (Sheath and Boom, 1985; De Rose *et al.,* 1995). This therefore reduces the input of organic material back into the soil profile. Secondly, easy and flat slopes will receive more solar radiation than steep slopes throughout the period of a year (this will be explained in more detail in Chapter 7), which when combined with more favourable moisture conditions, increases pasture production and the subsequent input of organic material into the soil profile. Gillingham *et al.* (1998) also reported higher clover growth on easy sites compared to steep sites which will increase the concentration of N in organic material entering the soil profile.

The similarity in total N levels between flat, southerly and easy sites indicates that the moisture and temperature regimes on flat sites are more closely related to southerly and easy sites, than to northerly and steep sites.

Two studies carried out by Cuff (1973) and McIntosh *et al.* (1981) examined the relative state of soil development on north and south aspects over sites with varying rainfalls. Below 700mm of average annual rainfall both north and south aspects were similarly developed (in terms of organic matter build up) due to soil moisture limiting biological activity and associated development equally on both aspects. In the 700-1000 mm rainfall range southerly aspects were more developed (with higher levels of organic matter) than northerly aspects. This was due to northerly aspects drying out more often and soil moisture becoming a limiting factor in soil development on these sites. In the 1000-1400 mm rainfall category the northerly aspects were more developed than the southerly aspects due to soil moisture not being a limiting factor and the higher amounts of solar radiation on the northerly faces driving the soil forming process faster. The results of the current trial (Figure 4.1) were consistent with these findings.

There was no significant effect of fertiliser addition (either P or N) on total N levels in the 0-37.5 mm soil depth. This is probably unsurprising as the rate of N addition (30 kg N/ha/yr) was very low in relation to the quantities of N cycling annually and the dry climate prevented P addition from stimulating large increases in clover growth and N fixation in the four years since the commencement of the trial.

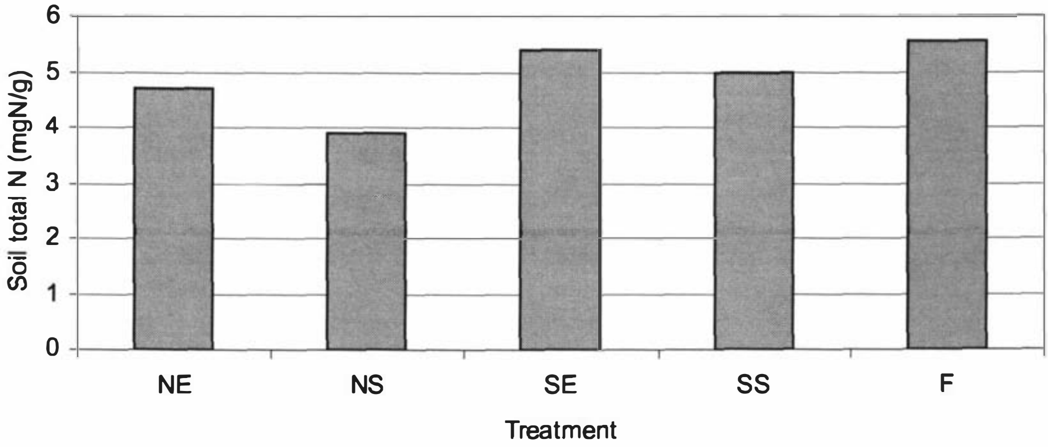


Figure 4.1 Total soil N averaged within each aspect and slope in the 0-37.5 mm depth.

The range of total soil N concentrations for the 37.5 - 75 mm depth was from 2.60 to 4.48 mgN/g on the HPNS sites in both control and plus-N plots and LPF plus-N sites respectively. This compares with the range from 3.62 to 5.90 mgN/g for the 0 – 37.5 mm depth (Tables 4.1 & 4.3). The higher concentrations of total N in the surface layers are to be expected and reflect higher concentrations of organic matter in the top layer due to additions of dead and decaying material. In an older soil this top layer, with a higher concentration of organic matter is likely to be deeper (Tonkin, 1985).

Table 4.3 Total soil N (mgN/g) in the 37.5-75 mm depth.

Treatment	**Control**	**Plus Nitrogen (30 kg N/ha)**
HPNE	3.36	3.54
LPNE	3.54	3.36
HPSE	3.68	4.44
LPSE	3.96	4.28
HPNS	2.60	2.60
LPNS	3.04	3.24
HPSS	3.38	3.56
LPSS	3.46	3.26
HPF	4.40	4.42
LPF	4.18	4.48

As in the 0 – 37.5 mm soil depth there was a significant difference in total N at the lower depth between the north and south aspects, and the easy and steep slopes. However in contrast to the top layer, at the lower depth there was also a significant difference between the easy and flat slopes, and the south and flat aspects, with soil on the flat slopes having significantly higher total N concentrations than the easy slopes and south aspects. Table 4.2 highlights this fact with the contrasts SE vs. SS and SS vs. F being significant at the lower depth, but not at the shallower depth.

This indicates that the flat sites are developed to a greater depth than the soils on other aspects and slopes. A possible explanation for this could be that soil erodes away from the steeper slopes more readily than the flat sites, thus causing the flat sites to have a deeper layer of more developed soil. Another factor is the lower dry matter production levels and inefficient nutrient cycling on the steep slopes compared to flat sites, leading to a smaller build up of organic matter and a subsequent shallower depth of development.

4.3.2 Total P

Total P levels in the 0-37.5 mm soil depth ranged from 0.51 to 0.88 mgP/g for the LPNE and LPSE plus-N sites respectively (Table 4.4). On all slopes and aspects the HP farmlets had significantly higher soil total P levels compared with the LP farmlets (Figure 4.2). The nitrogen fertiliser applications had no apparent effect on the total P concentration.

The total P levels are broadly comparable with those found by Moir (2000). Total P concentrations in Moir's (2000) study ranged from 0.40 to 0.86 mgP/g soil in the 0-75 mm depth. Due to the deeper soil sampling depth the results in that study are likely to be slightly lower than those in this study.

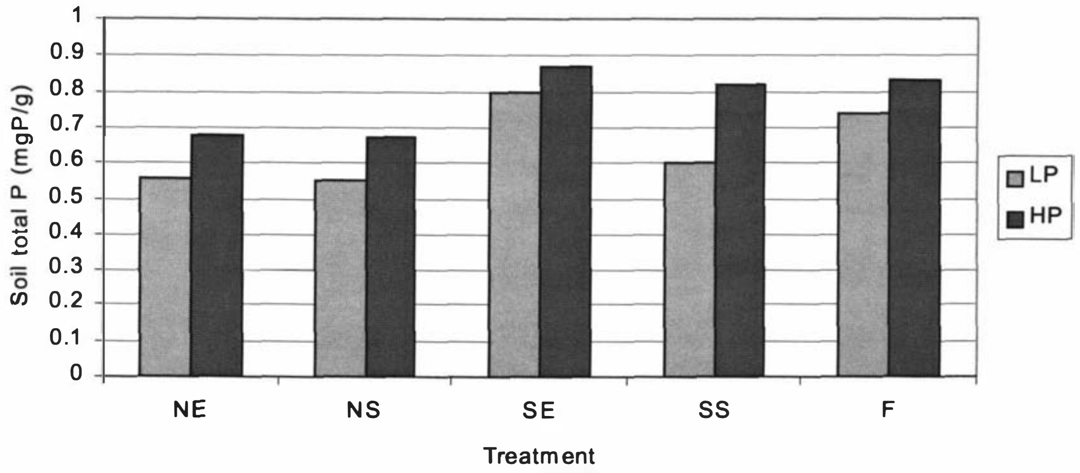


Figure 4.2 Total soil P averaged within slopes and aspects for LP and HP treatments in the 0-37.5 mm depth.

Table 4.4 Total soil P (mgP/g) in the 0-37.5 mm depth.

Treatment	**LP**	**HP**
NE +N	0.51	0.75
NE –N	0.60	0.61
SE +N	0.88	0.87
SE –N	0.72	0.87
NS +N	0.54	0.68
NS –N	0.56	0.65
SS +N	0.67	0.81
SS –N	0.53	0.82
F +N	0.78	0.86
F –N	0.70	0.79

Total soil P levels were significantly higher on southerly slopes compared to northerly slopes and were higher on easier slopes than steeper slopes (Tables 4.2 & 4.4).

It is the biological processes in soil that largely determine the concentration of total N. In contrast, the concentration of total P is influenced by the initial P content of the parent material, the addition of P-containing fertilisers and the transfer of P in animal dung (Gillingham, 1978; Rowarth, 1987; Saggar *et al.,* 1990).

If it is assumed that the P content of parent material was constant across the trial then much of the observed difference in total P levels between slopes and aspects may be due to animal transfer. The differences in total P levels found (Figure 4.2) are similar to those of Gillingham (1978) who found that P loss was greater on northerly slopes than on southerly slopes and was greater from steeper slopes than easier slopes. Gillingham's (1978) study also found that P built up on stock camp sites more on cooler southerly sites than warm northerly sites. Similar results have also been reported by Lambert (1977), Rowarth (1987) and Saggar *et al.* (1990).

Table 4.5 Total soil P (mgP/g) in the 37.5-75 mm depth.

Treatment	**LP**	**HP**
NE +N	0.42	0.58
NE –N	0.50	0.48
SE +N	0.67	0.66
SE –N	0.62	0.69
NS +N	0.44	0.46
NS –N	0.45	0.44
SS +N	0.44	0.52
SS –N	0.42	0.49
F +N	0.69	0.65
F –N	0.58	0.73

The total soil P concentrations in the 37.5 – 75 mm depth, displayed a similar pattern to those found in the 0-37.5 mm depth, with values ranging from 0.42 to 0.73 mgP/g for the LPNE and HPF sites respectively. However, the large application of phosphate fertiliser at the start of the trial had not had an effect on the total P results in this soil depth with no significant difference in soil total P between the LP and HP treatments. As with total N the total P concentrations were significantly lower at the greater depth, due to the addition of plant litter, animal dung and fertiliser to the soil surface.

4.4 CONCLUSIONS

The total soil N and P results provide an interesting comparison of the relative fertility and levels of soil development between the varying aspects, slopes and fertiliser regimes present on the trial site. The results indicate that the varying fertiliser regimes have had no effect on the total N concentration in the soil. It would be expected that the nitrogen fertiliser applications would not have had a significant effect on these results, due firstly to the low amount of N applied annually and secondly due to the dynamic nature of the N system, in which there can be large losses of inorganic N from the soil. However, the HP fertiliser regime might be expected to promote clover growth and subsequently increase the amount of total N in the soil through biological N fixation. The data suggest that this is not occurring on the trial. One explanation could be that four years is not enough time for there to be a detectable build up of N from biological fixation. A more likely reason is that the dry nature of the climate in this region restricts clover establishment and persistence due to a lack of moisture and in some cases excessively high temperatures on northerly slopes, which consequently limits N fixation. A more detailed discussion of the effect of climate on soil moisture and clover growth will be presented in later chapters.

As would be expected there was a significant difference in the total P concentration of the soil in the 0 – 37.5 mm depth between the LP and HP treatments, caused by the large application of P fertiliser before the trial began. There is however, no difference between the LP and HP treatments at the lower depth indicating that four years has not been long enough for this P fertiliser to move down through the soil profile via various biological and chemical processes.

The rate of biological reactions has a major role in determining the speed at which a soil develops, and the amount of energy inputs and available soil moisture are controlling factors in the rate of these reactions (Jenny, 1961; 1980). The contrasting slopes and aspects therefore, appear to provide sufficient variations in energy input and moisture to create significant differences in the levels of soil development and total N accumulation. The results indicate that soils on south-facing and flat sites have significantly higher levels of total N and P, and are hence, more fertile than soils on north-facing sites. The easy and flat sites also had higher levels of total N and P than steep sites and can be considered inherently more fertile.

The following chapters investigate how the contrasting topographies, micro-climates and the resulting soil properties described in this chapter interact to determine water and nutrient availability and pasture production.

CHAPTER 5

SOIL MEASUREMENTS AND RESULTS FOR THE TRIAL PERIOD

5.1 INTRODUCTION

The AgResearch grazing trial at Waipawa has demonstrated large differences in annual pasture production and seasonal growth rates between contrasting slopes and aspects (Gillingham *et al.,* 1998). As was highlighted in the previous chapter, these variations in pasture growth will result from an interaction of environmental factors and soil nutrient availability – which itself is largely a function of environmental conditions.

In order to devise fertiliser strategies that optimise economic returns and minimise environmental impacts, it is necessary to " disentangle" this complex interaction of soil fertility and environmental parameters. If this can be done, then it may be possible to identify these areas of the landscape, and those times of the year, when it is actually soil fertility that is constraining pasture production – rather than temperature, or the availability of soil water. Once these areas and times have been identified, fertiliser can be targeted so as to achieve the optimum result.

In the trial described in the following chapters, an attempt was made to separate out the effects of environment and soil nutrient availability on pasture growth rate. This was done by applying sufficiently high rates of N to pasture to ensure that it was non-limiting to pasture growth. As half the trial also had very high Olsen P levels it was hoped that all nutrient constraints to pasture growth would have been overcome on those sites, and any remaining differences in pasture production between sites would reflect the influence of environment.

Also, comparison of production in the presence of non-limiting nutrient availability with that of normal pasture would provide information on the extent to which nutrient availability is constraining pasture production in dry hill country.

5.2 MATERIALS AND METHODS

5.2.1 Pasture growth trial design

The existing design and site locations of the AgResearch pasture growth trial provided an ideal base for the nitrogen response trial, although the plus-N sites could not be used due to the scheduled application of N fertiliser in May. This left a total of 50 possible sites from which to choose the most uniform subset of 30 sites (based on soil analyses reported in the previous chapter).

The existing trial provided three main contrasts over which the major restrictions on pasture growth could be measured. These were phosphate status (high phosphate (HP) and low phosphate (LP)), aspect (North and South), and slope (steep (25° +), easy (15-20°) and flat (0-12°)). This gave a total of ten combinations of P status and topography. These were, Low P North Easy (LPNE), Low P North Steep (LPNS), High P North Easy (HPNE), High P North Steep (HPNS), Low P South Easy (LPSE), Low P South Steep (LPSS), High P South Easy (HPSE), High P South Steep (HPSS), Low P Flat (LPF), High P Flat (HPF). Throughout the remainder of the thesis, each of these combinations will be referred to as a "site".

Each of these sites was replicated three times to give a total of 30 locations. At each location, two 0.5 m^2 cages were used to measure pasture growth. One of the cages was used to measure pasture growth under the current soil fertility regime, while the other cage had 120 kg N/ha as urea applied to it, to allow growth under unlimiting N conditions. The cage locations were pretrimmed before cage placement and pasture was cut monthly (or when growth conditions permitted) and analysed.

The N on the N-unlimited cages was applied in three dressings of 40 kg N/ha. The first dressing was applied 2 weeks before cage placement, the second dressing applied at the time of the cage placement and the third dressing applied two weeks before the cages were cut. The reasoning behind the split dressings was firstly to minimise the risk of burning the grass through a too heavy application of N, and secondly to overcome any initial lag period in the response to nitrogen. Soil samples were taken from adjacent to the cage under which pasture growth was measured in the absence of added N fertiliser. Each sample comprised six cores that were taken to a depth of 75 mm at the start of each growth period. The sampling dates are reported in Table 5.1.

Table 5.1 Date of soil sample collection.

Sampling	Date of sample collection
1	3/3/99
2	9/4/99
3	11/5/99
4	9/7/99
5	4/9/99
6	12/10/99
7	16/11/99
8	12/1/00

In addition to the soil and pasture measurements made in the trial, rainfall was measured at the site on a daily basis. The monthly totals are presented in Table 5.2.

Table 5.2 Monthly rainfall for the trial period (mm).

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Tot
Rain-fall	122	122	66	64	75	38	40	21	178	17	120	6	869

5.2.2 Soil analyses

5.2.2.1 Soil moisture

A representative sample of the soil was weighed and placed in an oven at 105°C over night. The soil was then weighed again and the gravimetric soil moisture content was calculated from the difference in weight.

5.2.2.2 Ammonium-N and Nitrate-N

A 3 g sample of fresh, field-moist soil was placed into a centrifuge tube and 30 ml of 2M KCL was added to the soil. The mixture was shaken for 30 minutes on an end-over-end shaker and centrifuged at 9000 rpm for 1 minute. The solution was then decanted off and filtered through Whatman No. 1 filter paper. The samples were analysed on an autoanalyser for ammonium-N and nitrate-N concentrations (Kamphake *et al*, 1967; Searle, 1975, 1984). The results from the soil moisture analyses were then used to calculate the ammonium-N and nitrate-N concentrations in the oven dry soil using the adjusted soil weights.

5.2.2.3 Mineralisable N

A slightly modified method to that used by Keeney and Bremner (1966) was used in this study. A 5 g sample of fresh, field moist soil was placed into a centrifuge tube and 20 ml of distilled water was added to the soil. The mixture was incubated at 35°C for 15 days in the sealed tube. Ten ml of 3M KCL was then added to the tube which was shaken for 20 minutes on an end-over-end shaker and centrifuged at 8000 rpm for 5 minutes. The solution was decanted and filtered through Whatman No. 1 filter paper. The samples were analysed on an autoanalyser for ammonium-N and nitrate-N concentrations (Kamphake *et al*, 1967; Searle, 1975, 1984). The results from the soil moisture analyses were then used to calculate the ammonium-N and nitrate-N concentrations in oven-dry soil using the adjusted soil weights. The mineralisable N content was calculated by subtracting the initial quantities of ammonium-N and nitrate-N in the field moist soil from the quantities of ammonium-N and nitrate-N present after incubation.

5.2.2.4 Olsen P

A separate soil sample of six cores was taken from each site at the end of the trial period to analyse for Olsen P. From each of these samples a 1 g sample of air dried, sieved soil was placed into a centrifuge tube and 20 ml of freshly prepared 0.5M $NaHCO_3$, adjusted to pH 8.5 was added. The mixture was shaken on an end-over-end shaker for 30 minutes. The mixture was then centrifuged at 9000 rpm for 1 minute and the solution was decanted and filtered under suction through a Whatman No. 6 filter paper. A 4 ml aliquot of the filtrate was then placed into a 50 ml volumetric flask and the Olsen P value measured using the colorimetric procedure of Murphy and Riley (1962).

5.2.2.5 Soil Temperature

Sampac Temprecord general multitrip soil temperature probes were placed throughout the trial on NE, NS, SE, and SS slopes. The probes were placed at a soil depth of 100 mm and recorded the soil temperature every 30 minutes throughout the period of the trial. The results were averaged for every day.

5.3 RESULTS AND DISCUSSION

Samples were statistically analysed using a multi-factorial unbalanced analysis of variance.

5.3.1 Soil Moisture

The average gravimetric soil moisture contents for each of the 8 samplings are presented in Table 5.3 and Figure 5.1. There were large variations in soil moisture between slopes and aspects at any one time, and also between the sampling times. The values range from a minimum of 9.2 % for LPNS sites at sampling 6, collected in mid October, to a maximum of 65.1 % for LPSE sites at sampling 4, in the middle of July. The largest variation with time in soil moisture within a site was on the LPSS sites which had a maximum gravimetric soil moisture content of 57.0 % and a minimum of 20.5 %, a difference of 36.5 %. The lowest variation with time came on the HPNS sites, which had a maximum gravimetric soil moisture content of 31.2 % and a minimum of 11.7 %, a difference of 19.5 %.

Table 5.3 Gravimetric soil moisture (%) (0 – 75mm depth) on sites of contrasting slope, aspect and P status at each of the 8 sampling times.

Sample	1	2	3	4	5	6	7	8
LPNE	20.9	36.8	44.3	39.0	22.1	18.0	20.4	27.1
LPNS	21.7	30.0	30.1	23.6	13.4	9.2	16.8	16.0
LPSE	34.8	56.8	51.7	65.1	45.5	41.6	39.0	29.7
LPSS	31.8	49.0	45.9	56.9	43.1	33.6	29.8	20.5
HPNE	22.4	37.0	43.1	37.1	23.4	18.6	30.0	23.5
HPNS	19.7	30.7	31.2	29.8	14.2	11.7	20.9	13.4
HPSE	31.9	43.6	48.4	47.8	38.3	32.0	26.8	21.1
HPSS	28.5	52.1	55.6	50.6	46.6	36.7	29.4	21.1
LPF	34.0	49.8	52.3	55.4	37.4	28.5	28.3	19.3
HPF	27.3	49.8	49.0	49.3	31.7	25.3	27.1	19.1

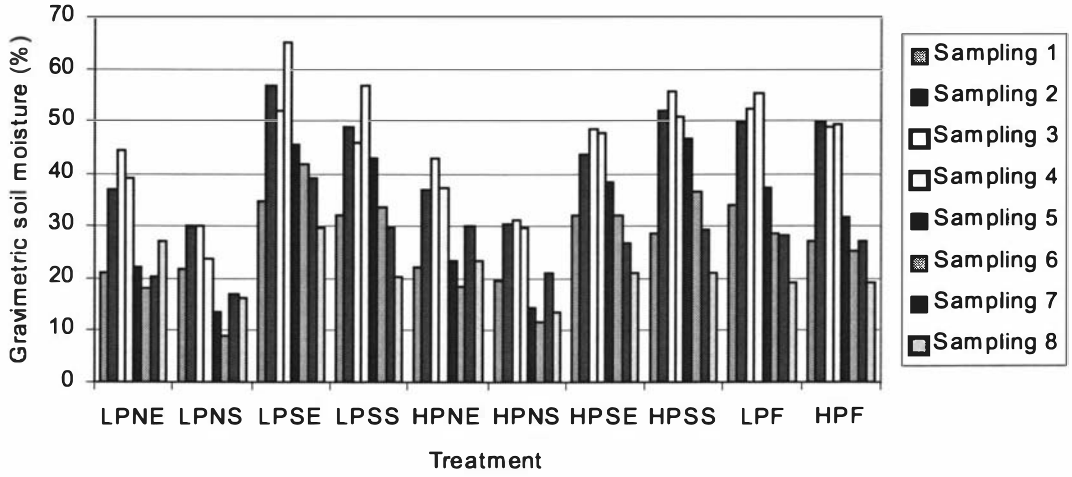


Figure 5.1 Gravimetric soil moisture (%) (0 – 75mm depth) on sites of contrasting slope, aspect and P status at each of the 8 sampling times.

In general, the soil moisture content on the southerly and flat aspects varied more with time than on the northerly aspects, and the southerly and flat aspects had significantly higher levels of soil moisture than the northerly aspects at all times of the year except for sampling 8 in mid summer (Table 5.4). The southerly and flat sites however, had similar gravimetric soil moisture contents to each other throughout the year, except for samplings 5 and 6 in early and mid spring, when moisture levels on the southerly sites were significantly higher.

These contrasts are likely to be due to two factors. The first is that the soil water holding capacity is likely to be higher in the southerly and flat sites due to a higher soil organic matter content, as shown in Chapter 4. This would therefore, imply that there is more water in the soil on these sites in winter, and therefore, more scope for larger variations throughout the year. Secondly, the northerly aspects receive more solar radiation throughout the year and therefore have higher evapotranspiration rates than the southerly and flat aspects. This will have caused the moisture levels on the northerly aspects to be lower. The significantly higher soil moisture levels on southerly sites compared to flat sites in samplings 5 and 6 is also likely to be due to the flat sites receiving greater solar radiation over this period. These aspects will be discussed in more detail in Chapter 7 in relation to the simulation modeling exercise.

Table 5.4 Statistical analysis of the soil moisture data for the 8 sampling times.

Contrast	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Phosphate	-	-	-	*	-	-	-	-
NE vs. NS	-	-	**	**	**	**	-	**
NE vs. SE	**	**	-	**	**	**	-	-
NE vs. SS	*	**	*	**	**	**	-	-
NE vs. F	*	**	*	**	**	**	-	*
NS vs. SE	**	**	**	**	**	**	*	**
NS vs. SS	*	**	**	**	**	**	-	*
NS vs. F	**	**	**	**	**	**	-	-
SE vs. SS	-	-	-	-	-	-	-	-
SE vs. F	-	-	-	-	*	**	-	*
SS vs. F	-	-	-	-	**	**	-	-
North vs. South	**	**	**	**	**	**	*	-
Easy vs. Steep	-	-	*	*	-	**	-	**
North vs. Flat	**	**	**	**	**	**	-	-
South vs. Flat	-	-	-	-	**	**	-	-
Easy vs. Flat	-	*	-	-	-	-	-	*
Steep vs. Flat	-	**	**	**	*	*	-	-

* = $P < 0.05$; ** = $P < 0.01$.

The general pattern displayed by all the sites, is an increase in soil moisture from the start of the trial in March until sampling 4 at the beginning of July. This is due to higher rainfall inputs and lower evapotranspiration rates. Thereafter, moisture levels in all of the sites declined as a result of decreasing rainfall and increasing evapotranspiration rates. The northerly sites dried out quicker than the other sites for reasons mentioned above and reached a minimum in sampling 6 near the middle of October. The large rainfall events in November and January combined with very high evapotranspiration rates caused the soil moisture levels on the northerly sites to fluctuate after this point.

Although after sampling 4, the moisture levels on the southerly and flat sites decreased there was no increase in soil moisture levels at sampling 6 with the increased summer rainfall. This may be caused by a factor such as hydrophobicity, which reduced the ability of rain to enter the soil. This concept will be discussed later in Chapter 7.

The periods of the year when there were the largest significant variations in gravimetric soil water content between sites were through winter and spring. During the winter the soils reached field capacity, and due to the much higher water holding capacity of the southerly and flat sites, there were a number of significant contrasts between the sites at this time, with the northerly sites having significantly lower gravimetric soil moisture contents than the southerly and flat sites, except for sampling 3 when there was no significant difference between NE and SE sites (Table 5.4). During the spring, the soils dried, and due to the northerly sites having higher evapotranspiration rates than the flat sites which in turn had higher rates than the southerly sites, statistically significant differences in soil moisture contents developed between these varying slopes and aspects.

5.3.2 Soil Temperature

In Figure 5.2 the average soil temperature (for that particular day) is presented for every fifteenth day throughout the trial. The soil temperature data are presented in this way to enable the main trends and comparisons between sites to be observed more easily. For interest however, the detailed daily data are presented in Figure 5.3 for one site (NE). This data set indicates that although there are clear seasonal trends, there is considerable variation in soil temperature from day to day.

The data in Figure 5.2 suggest that there was no difference in temperature between the SE and SS sites throughout the year, however the northerly sites were at a higher temperature than the southerly sites at all times of the year, with the NS sites higher than the NE sites, particularly in the winter. The general pattern followed by all of the sites was that the soil temperature remained relatively constant from the start of the trial through to the beginning of April. The temperature then underwent a marked drop until mid April where it stayed reasonably constant until the end of May. There was then another marked drop and the temperature remained at its lowest until the start of August. It then steadily increased until mid January, where it stayed constant until the end of February. As mentioned above, this trend is only a general pattern as there were large fluctuations on a daily basis as shown in Figure 5.3. Of particular note was the dramatic drop in temperature on 1 January, 2000. This was caused by a severe hail storm, which dropped the temperature close to mid winter levels.

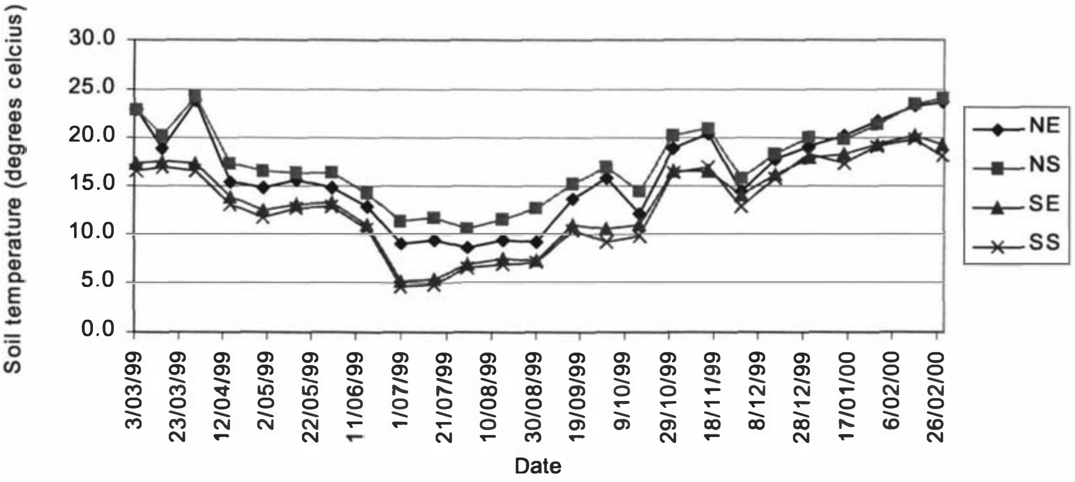


Figure 5.2 Average daily soil temperatures (0 –100mm depth) for individual days at 15-day intervals for the period of the trial.

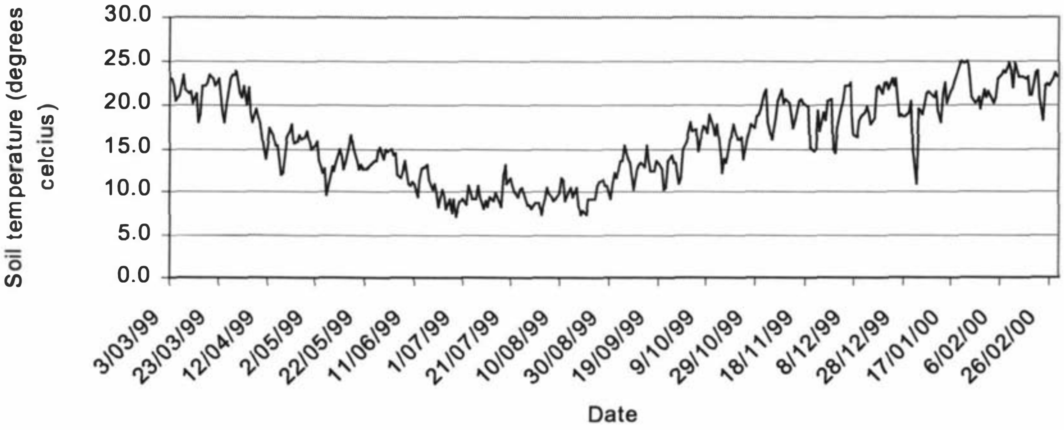


Figure 5.3 Average daily soil temperatures (0 –100mm depth) for the NE sites.

5.3.3 Ammonium-N and Nitrate-N

The results displayed in Tables 5.5 and 5.6 and Figure 5.4 show the soil ammonium-N and nitrate-N concentrations at the 8 sampling times. Soil ammonium-N concentrations ranged from 0.6 μg/g in the HPSE sites in sampling 8 (January) to 55.3 μg/g in the LPNE sites in sampling 4 (July). Soil nitrate-N concentrations ranged from 0 μg/g for most sites in sampling 6 (October) to 25.8 μg/g in the LPF sites in sampling 4 (July).

Whilst there appeared to be some large differences between sites within a sampling time, the statistical analysis of the data (Tables 5.7 and 5.8) suggest that there were very few statistically significant differences in soil ammonium-N and nitrate-N between sites throughout the 8 samplings. This was largely due to the large variation between replicate cage locations within sites. Figures 5.5 and 5.6 show the frequency distributions of the ammonium-N and nitrate-N levels indicating the large range in values observed. Most of the ammonium-N values (Figure 5.6) fell within 3 – 9 µg N/g, but there was one value in the 100-200 µg/g range and four in the 50-100 µg/g range. These high outlying values are likely to be due to the soil samples being taken inadvertently from urine spots.

Table 5.5 Soil ammonium-N concentrations (µg N/g) (0 – 75mm depth) on sites of contrasting slope, aspect and P status at each of the sampling times.

Sample	1	2	3	4	5	6	7	8
LPNE	10.4	15.5	32.0	55.3	6.6	3.9	5.9	1.5
LPNS	5.4	6.1	6.1	3.3	9.8	3.1	4.5	1.6
LPSE	6.1	10.1	5.2	5.3	8.0	7.3	6.6	1.1
LPSS	5.5	5.2	4.4	3.2	7.7	13.2	4.1	1.0
HPNE	9.3	5.9	31.0	5.2	10.4	19.2	5.2	1.1
HPNS	5.9	5.8	3.7	3.6	4.8	3.8	13.5	1.2
HPSE	6.1	5.3	5.1	3.3	9.6	5.0	6.0	0.6
HPSS	8.6	6.1	6.7	4.6	8.5	6.4	5.5	0.8
LPF	9.4	10.3	8.4	23.1	7.4	4.3	5.7	2.0
HPF	5.1	6.5	25.5	12.5	7.9	5.4	5.5	4.5

Table 5.6 Soil nitrate-N concentrations (µg N/g) (0 – 75mm depth) on sites of contrasting slope, aspect and P status at each of the sampling times.

Sample	1	2	3	4	5	6	7	8
LPNE	9.8	11.3	11.6	15.6	3.3	0.0	4.9	10.5
LPNS	8.2	9.5	8.6	11.8	1.7	0.0	3.1	11.4
LPSE	7.4	9.9	13.4	23.6	4.1	0.0	2.8	10.1
LPSS	6.7	6.0	9.6	17.9	2.1	0.0	3.0	6.8
HPNE	19.1	11.7	12.1	14.0	2.2	6.7	3.2	8.7
HPNS	11.4	11.0	8.6	13.7	4.9	0.0	8.0	9.3
HPSE	4.3	6.7	9.1	15.3	1.8	0.0	3.8	9.4
HPSS	8.5	6.7	11.3	14.7	2.1	0.0	2.1	7.8
LPF	12.0	14.5	14.9	25.8	5.1	0.4	14.5	8.7
HPF	7.7	11.8	21.6	18.2	6.5	2.1	3.1	14.5

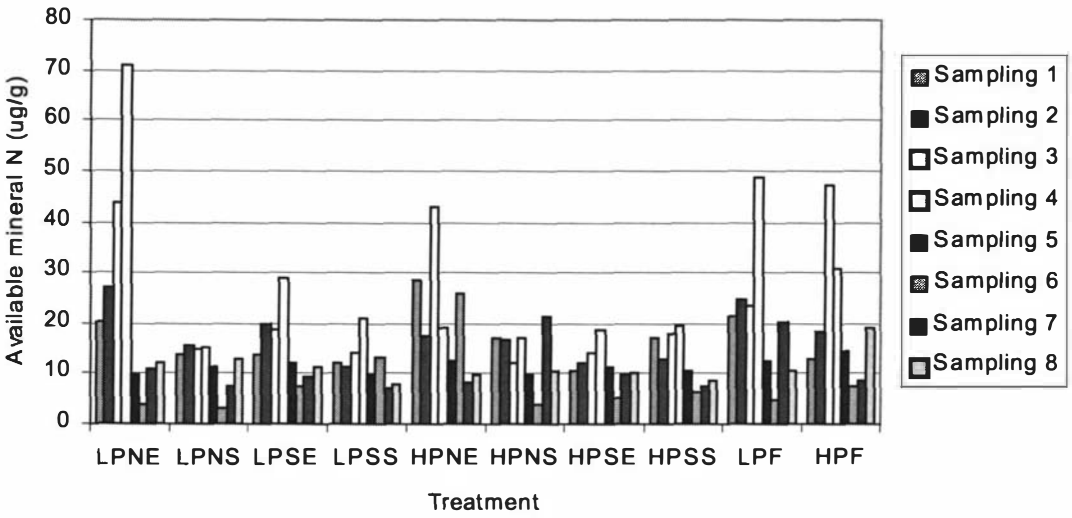


Figure 5.4 Soil mineral N (ammonium-N + nitrate-N) (0 – 75mm depth) at each site at each of the sampling times.

Table 5.7 Statistical analysis of the soil ammonium-N data for each of the samplings.

Contrast	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Phosphate	-	-	-	-	-	-	-	-
NE vs. NS	*	-	-	-	-	-	-	-
NE vs. SE	*	-	-	-	-	-	-	-
NE vs. SS	-	-	-	-	-	-	-	-
NE vs. F	-	-	-	-	-	-	-	-
NS vs. SE	-	-	-	-	-	-	-	-
NS vs. SS	-	-	-	-	-	-	-	-
NS vs. F	-	-	-	-	-	-	-	-
SE vs. SS	-	-	-	-	-	-	-	-
SE vs. F	-	-	-	-	-	-	-	*
SS vs. F	-	-	-	-	-	-	-	*
North vs. South	-	-	-	-	-	-	-	-
Easy vs. Steep	-	-	-	-	-	-	-	-
North vs. Flat	-	-	-	-	-	-	-	*
South vs. Flat	-	-	-	-	-	-	-	*
Easy vs. Flat	-	-	-	-	-	-	-	*
Steep vs. Flat	-	-	-	-	-	-	-	*

* = $P < 0.05$; ** = $P < 0.01$.

Table 5.8 Statistical analysis of the soil nitrate-N data for each of the samplings.

Contrast	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Phosphate	-	-	-	*	-	-	-	-
NE vs. NS	-	-	-	-	-	-	-	-
NE vs. SE	*	-	-	-	-	-	-	-
NE vs. SS	*	-	-	-	-	-	-	-
NE vs. F	-	-	-	*	-	-	-	-
NS vs. SE	-	-	-	*	-	-	-	-
NS vs. SS	-	-	-	-	-	-	-	-
NS vs. F	-	-	-	**	-	-	-	-
SE vs. SS	-	-	-	-	-	-	-	-
SE vs. F	-	-	-	-	-	-	-	-
SS vs. F	-	-	-	*	*	-	-	*
North vs. South	*	-	-	*	-	-	-	-
Easy vs. Steep	-	-	-	-	-	-	-	-
North vs. Flat	-	-	-	**	-	-	-	-
South vs. Flat	-	-	-	-	*	-	-	*
Easy vs. Flat	-	-	-	-	-	-	-	-
Steep vs. Flat	-	-	-	**	*	-	-	-

* = $P < 0.05$; ** = $P < 0.01$.

The soil nitrate-N values (Figure 5.7) are less scattered with a reasonably even distribution from 1-13 µg/g. However, there were still outliers with seven values between 25 and 50 µg/g. So whilst on average there are apparent differences between sites, the large variations between replicates means that there are no statistically significant differences. Such large variation has been observed by many researchers and affects the reliability of soil ammonium-N and nitrate-N levels as predictors of plant available N (Ball and Field, 1982; Craighead and Clark, 1989). As mentioned in Chapter 2, the N cycle is a very complex and dynamic system with many inputs and losses, particularly from animal urine, which creates "hot spots". This leads to the inorganic N pool (consisting of ammonium-N and nitrate-N) fluctuating markedly over time with the level of N depending on whether there have been more inputs or losses from the inorganic pool.

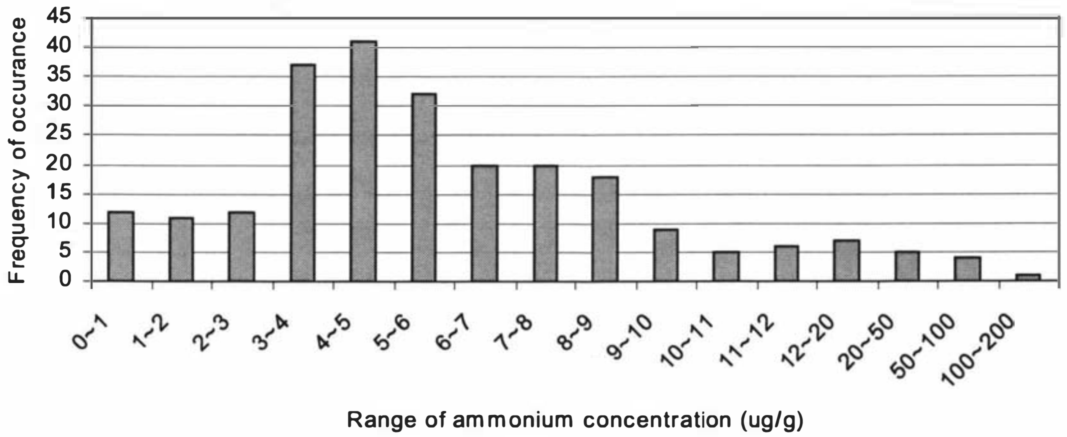


Figure 5.5 Frequency distribution of measured ammonium-N concentrations from all replicate cage sites and sampling times. (Note change in scale at 12 on horizontal axis).

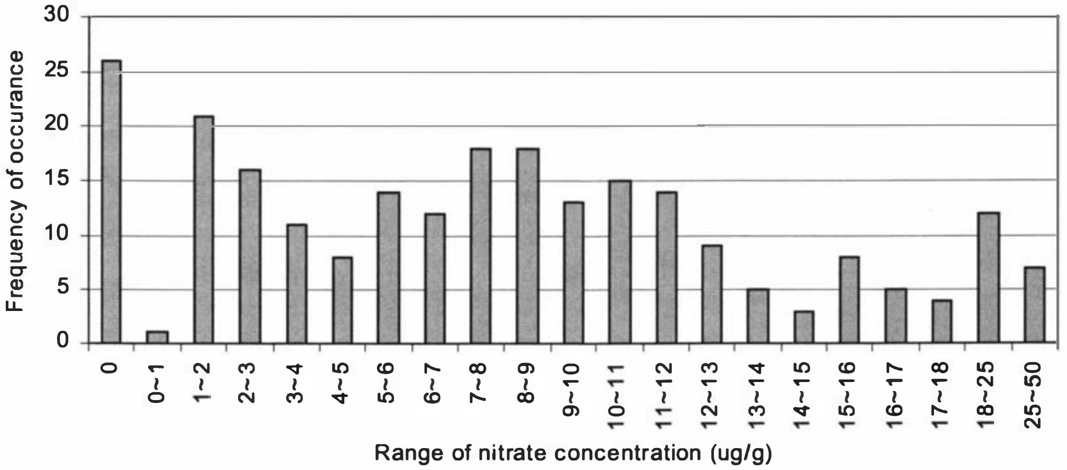


Figure 5.6 Frequency distribution of measured nitrate-N concentrations from all replicate cage sites and sampling times. (Note change in scale at 18 on horizontal axis).

Bearing in mind the variation between replicates, it is still possible to see a pattern developing in the total mineral N (ammonium-N + nitrate-N) results displayed in Figures 5.4 and 5.7 and the soil nitrate-N results in Table 5.6. There are no major variations between sampling times for ammonium-N except for a major fall in sampling 8 (January). However, nitrate-N results gradually increased over the first 4 samplings, and then declined and reached a minimum in sampling 6 (October) before increasing again for samplings 7 (November) and 8. This is a similar pattern to that found by Ball and Field (1982).

The gradual increase in mineral N up until mid winter would be expected. The mineralisation process continues at all times down to 0°C (Stanford *et al.,* 1973), and although the process slows down as soil temperatures decrease the rate of uptake by pasture also decreases. Thus, the mineralisation rate exceeds the uptake rate and mineral N increases. Other losses such as denitrification and leaching are likely to increase over this period as soil moisture and rainfall increase, however the mineralisation rate apparently still exceeds the losses. The build up is mainly evident in the quantities of nitrate-N, as ammonium-N is readily converted to nitrate-N unless it is taken up by plants or lost via volatilisation (Stanford *et al.,* 1973; Steele, 1982).

As soil temperatures increase at the start of August, the rate of mineralisation will also increase due to the mineralisation process being directly related to temperature (Kai *et al.,* 1969; Stanford *et al.,* 1973). However, soil mineral N values dropped over samplings 5 (September) and 6 (October) and the soils at most of the sites recorded zero soil nitrate-N at sampling 6. Samplings 5 and 6 were during spring when pasture growth rates are generally at their highest. Therefore, although mineralisation rates at this time are high, the pasture N uptake exceeds the mineralisation rate, the mineral N pool decreases, and pasture growth becomes limited by N mineralisation rates. Similar findings have been recorded by Sherlock and O'Connor (1973), Ball *et al.* (1976), Luscombe (1980) and Ball and Field (1982). Further discussion of this point is presented in Chapter 6.

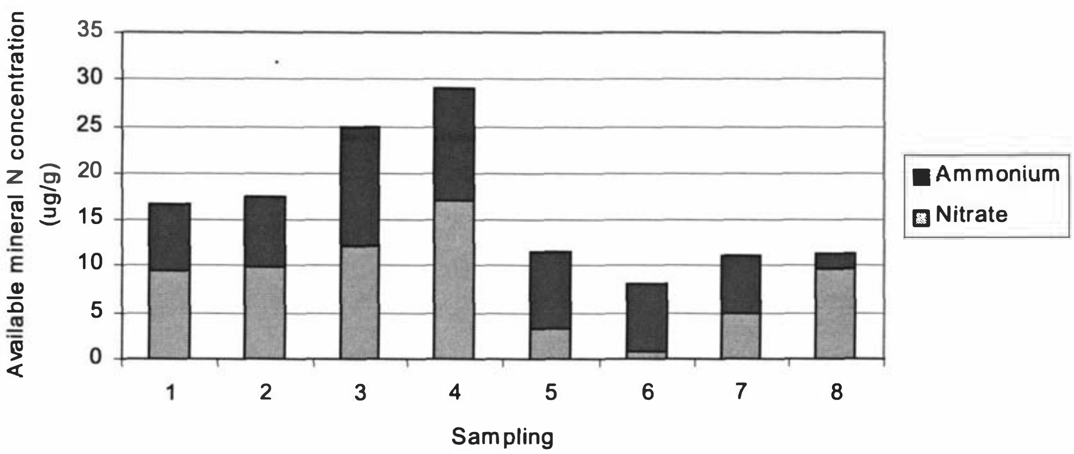


Figure 5.7 Average available mineral N (μg N/g) (0 – 75mm depth) averaged over all sites for the 8 sampling times.

5.3.4 Olsen P

Olsen P values ranged from 17 (μg/g) for the LPNE sites to 42 (μg/g) for the HPNS and HPSS sites, with the high P sites having statistically significantly higher levels than the LP sites (Tables 5.9 & 5.10). The LP sites generally have similar Olsen P levels in the range of 17-19 except for the LPSS sites which have a higher value of 26. Of note in the HP sites is that the steep slopes have significantly higher values, than the easy and flat slopes. This is thought to be caused by the steep slopes having a much higher stone content than the other slopes. This would cause the large application of 500 kg P/ha before the trial to have a larger effect on Olsen P values, due to the lesser quantity of soil particles to which it was applied.

The difference between the HP and LP sites is not as great as was found in other testing at the site. Average values of 10 for the LP sites and 28 for the HP sites (measured in September 1999) Gillingham (pers comm.) were for paddock averages, and measured volumetrically. Without corrections for bulk density and a greater number of measurements taken from a wider area, not too many conclusions can be drawn from the discrepancies.

Table 5.9 Average Olsen P results (0 – 75mm depth) for each site.

Site	**Olsen P (μg/g)**
LPNE	17
LPNS	19
LPSE	18
LPSS	26
HPNE	24
HPNS	42
HPSE	28
HPSS	42
LPF	19
HPF	35

Table 5.10 Statistical analysis of the Olsen P results for the varying slopes and aspects.

Contrast		Level of significance
Phosphate:	(LP<HP)	**
NE vs. NS:	(NE<NS)	*
NE vs. SE		-
NE vs. SS:	(NE<SS)	**
NE vs. F:	(NE<F)	*
NS vs. SE:	(NS>SE)	*
NS vs. SS		-
NS vs. F:	(NS>F)	*
SE vs. SS:	(SE<F)	**
SE vs. F		-
SS vs. F:	(SS>F)	**
North vs. South		-
Easy vs. Steep:	(E<S)	**
North vs. Flat		-
South vs. Flat		-
Easy vs. Flat		-
Steep vs. Flat:	(S>F)	*

* = $P < 0.05$; ** = $P < 0.01$.

5.3.5 Mineralisable Nitrogen

The results displayed in Table 5.11 and Figure 5.8 show the average mineralisable N levels for each site over the 8 sampling times. The values range from a minimum of 50.7 (μg/g) for the LPNS sites at sampling 6 (October) to a maximum of 306.5 (μg/g) for the LPF sites at sampling 4 (July). The values are generally lower than those found by Moir (2000) who sampled only reasonably flat fertile sites, although the range of values is similar. The values are higher than those found by Keeney and Bremner (1966), however they sampled to 150 mm soil depth. Therefore, although the values are spread over a wide range they are comparable with values found by other authors.

Table 5.11 Soil mineralisable N concentrations (μg/g) (0 – 75mm depth) on sites of contrasting slope, aspect and P status at each of the 8 sampling times.

Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LPNE	143.7	168.1	149.3	151.7	89.6	93.0	97.9	121.1
LPNS	81.9	91.1	68.7	76.8	75.3	50.7	63.6	81.7
LPSE	184.2	208.7	155.0	208.6	164.4	184.4	175.3	130.7
LPSS	128.4	150.2	122.7	142.0	134.1	65.7	87.2	100.6
HPNE	109.2	140.2	121.2	123.0	98.2	105.9	128.0	113.3
HPNS	84.0	108.8	77.4	100.5	94.0	66.8	75.8	93.6
HPSE	161.0	145.0	163.3	153.4	113.9	135.6	93.6	86.3
HPSS	158.3	145.7	124.9	111.9	132.8	134.7	110.5	94.5
LPF	198.6	240.5	195.9	306.5	181.3	111.9	157.6	133.3
HPF	159.9	177.3	191.9	263.2	143.6	122.4	151.1	148.2

The statistical analysis of the results in Table 5.12 indicates that flat sites have significantly higher mineralisable N values than northerly sites at all times of the year except for sampling 6 (October). Flat sites also have significantly higher levels of mineralisable N than steep sites throughout most of the year. These two contrasts are largely influenced by the NS sites which have significantly lower levels of mineralisable N than the flat sites at every sampling time. In general, the flat sites had the highest mineralisable N values followed by the southerly sites then the northerly sites. Statistically however, the southerly sites only have significantly higher levels of mineralisable N than the northerly sites in samplings 5 (September) and 6 (October) and the flat sites only have significantly higher levels of mineralisable N than the southerly sites in samplings 4 (July) and 8 (January).

Moir (2000) found that mineralisable N values increased as the P fertility increased due to increased clover growth. However, as with the levels of total N presented in Chapter 4, there was no significant effect of phosphate addition on levels of mineralisable N. Therefore, it would appear that either there has not as yet been enough phosphate-induced clover growth to increase the mineralisable N status of the HP sites, or that the dry nature of the country limits clover growth so much that P is not a limiting factor. Findings by Gillingham *et al.* (1998) show that the HP treatment has caused measurable increases in clover growth on NE and southerly sites suggesting that with time, increases in mineralisable N levels, as a result of P application, may become apparent.

Table 5.12 Statistical analysis of the mineralisable N data for each of the sampling times.

Contrast	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Phosphate	-	-	-	-	-	-	-	-
NE vs. NS	-	-	-	-	-	-	-	-
NE vs. SE	-	-	-	-	-	*	-	-
NE vs. SS	-	-	-	-	-	-	-	-
NE vs. F	*	-	-	**	*	-	-	-
NS vs. SE	**	*	*	*	-	**	*	-
NS vs. SS	*	-	-	-	-	-	-	-
NS vs. F	**	**	**	**	*	*	**	**
SE vs. SS	-	-	-	-	-	*	-	-
SE vs. F	-	-	-	*	-	-	-	-
SS vs. F	-	-	*	**	-	-	*	*
North vs. South	**	-	-	-	*	**	-	-
Easy vs. Steep	*	-	*	-	-	**	*	-
North vs. Flat	**	*	**	**	**	-	*	*
South vs. Flat	-	-	-	**	-	-	-	*
Easy vs. Flat	-	-	-	**	-	-	-	-
Steep vs. Flat	**	*	**	**	*	-	**	**

$* = P < 0.05$; $** = P < 0.01$.

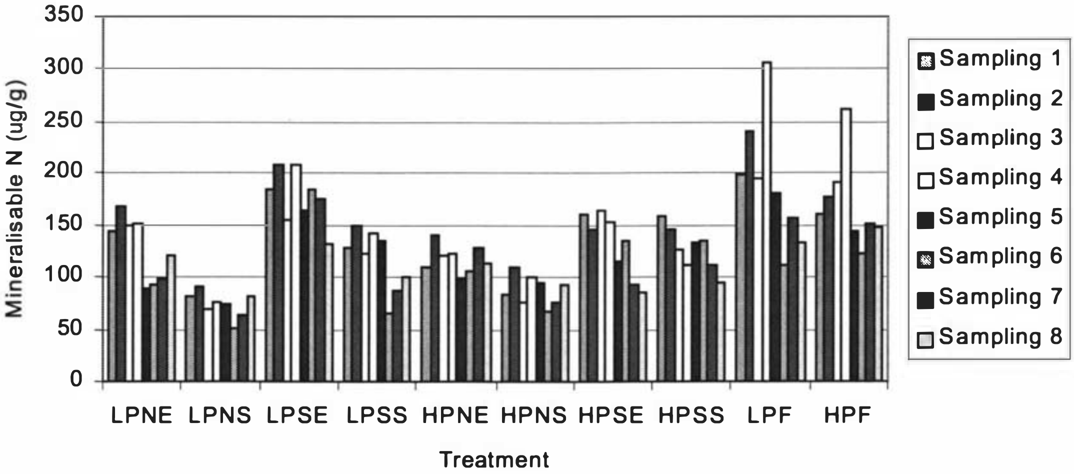


Figure 5.8 Soil mineralisable N (μg/g) (0 – 75mm depth) values on sites of contrasting slope, aspect and P status at each of the 8 sampling times.

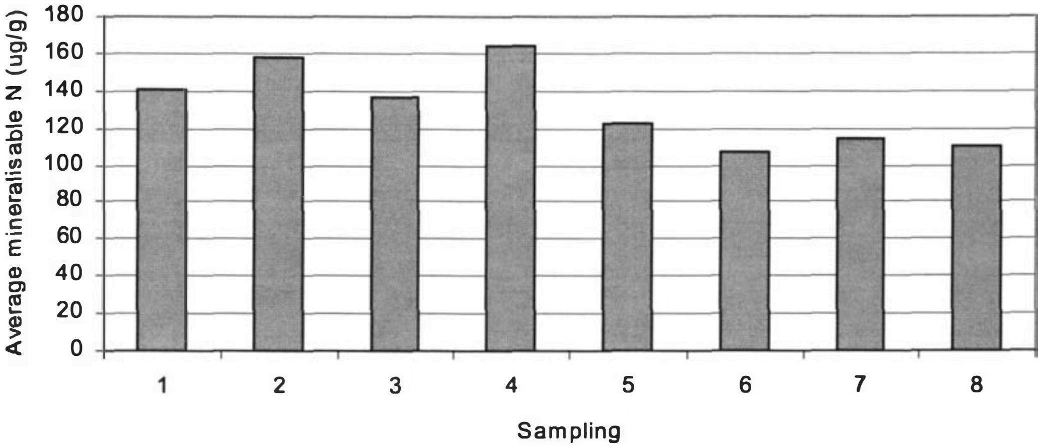


Figure 5.9 Mineralisable N values (0 – 75mm depth) averaged across all sites for each sampling time.

The within-site variations over time throughout the 8 samplings (Figure 5.8) show a slight pattern of increasing soil mineralisable N until sampling 4 (July) and then decreasing thereafter, with the highest values recorded at each site occurring within the first 4 samplings (March - July). Figure 5.9 highlights this trend, showing the mineralisable N values averaged across all sites for each sampling period. The mineralisable N test is essentially a reflection of the organic matter status of the soil (Sierra 1996), and the within-site variations over time suggest that the organic N status of the soil is therefore changing throughout the year.

Keeney and Bremner (1966) found when developing the mineralisable N test, that as soil was dried, mineralisable N values increased. To investigate whether there was a similar relationship in the current trial mineralisable N levels were regressed against gravimetric soil moisture over time at each site (Table 5.13). Some of the relationships were very weak and non-significant (HPNS & HPSS), but of note is the fact that all of the regression slopes were positive and some of the relationships were strong (LPNE & LPF). There was therefore, an opposite effect to that found by Keeney and Bremner (1966) with mineralisable N levels decreasing as soil moisture decreased. Reasons for this will be discussed below.

Table 5.13 Regressions of soil moisture (x) and mineralisable N values (y) within each site for the period of the trial.

Site	Equation	R^2 value
LPNE	$y = 2.9x + 42.4$	0.53
LPNS	$y = 1.2x + 49.2$	0.23
LPSE	$y = 2.8x + 48.8$	0.35
LPSS	$y = 1.9x + 42.1$	0.34
HPNE	$y = 1.9x + 61.3$	0.42
HPNS	$y = 1.2x + 61.2$	0.09
HPSE	$y = 2.3x + 48.5$	0.26
HPSS	$y = 0.7x + 99.3$	0.07
LPF	$y = 5.7x - 26.7$	0.65
HPF	$y = 2.8x + 73.7$	0.47

Closer examination of the data shows that the soil moisture was inversely related to soil temperature (Figures 5.10 and 5.11). Therefore, as soil temperatures increased soil moisture generally decreased, and vice versa.

Many studies have shown that the mineralisation of N is related to soil temperature, with net mineralisation increasing as temperature increases (Kai *et al.,* 1969; Campbell and Biederbeck, 1972; Stanford *et al.,* 1973; Ross and Bridger, 1977; Carran, 1979; Ledgard *et al.,* 1989; Clough *et al.,* 1998). Thus, soil samples collected after a warm, drying spell will have low moisture contents and also will have a depleted pool of mineralisable N due to the accelerated mineralisation occurring prior to soil sampling.

The theory postulated above, explains why the highest mineralisable N values were all recorded in the first 4 samplings, when soil temperatures were decreasing. After this point, soil temperatures increased, which in turn increased mineralisation rates and decreased the remaining mineralisable N pool. Carran (1979) reported that mineralisation rates undergo a massive increase at the start of spring to provide N for the spring flush.

Another point to note is the significant difference that appeared between the north and south aspects for samplings 5 and 6 (September and October) (Table 5.12). Lambert (1977) found that mineralisation rates were much higher on northerly faces than southerly faces. This would cause the northerly mineralisable N pools to decrease more rapidly than on southerly aspects. This effect is likely to be more prominent in the spring when the difference in soil temperature between the aspects is greatest (Figure 5.2). The differences in temperature regimes, soil moisture levels and energy inputs between the aspects is a key feature of the study and will be discussed and explained in further detail in later chapters.

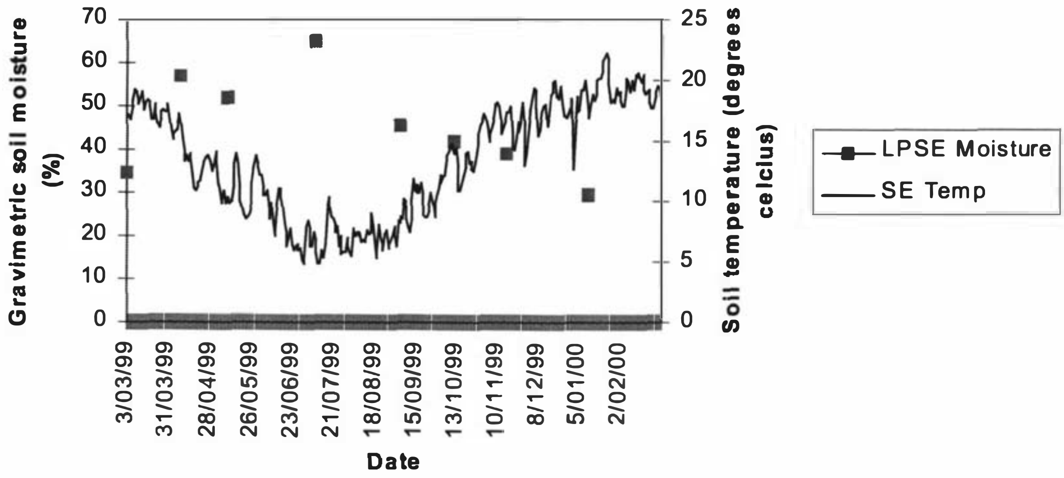


Figure 5.10 Relationship between soil moisture and soil temperature throughout the year on LPSE sites.

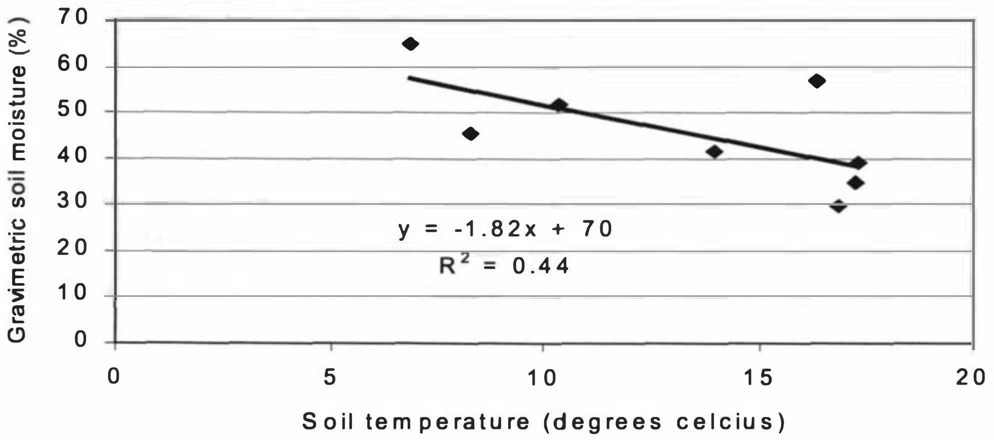


Figure 5.11 Graph showing the relationship between soil moisture and soil temperature for the LPSE site over the period of the trial.

In Table 5.13 discussed above, the relationships between soil mineralisable N and gravimetric soil moisture content were presented for each site separately over time. If alternatively, the mineralisable N and soil moisture data collected over the 8 samplings are combined to give an average value for each site (and replicate) and then the data for all sites are combined (Figure 5.12) there is an even stronger positive relationship between soil moisture and mineralisable N. However, this is likely to be due to a confounding effect by a number of factors. The first factor as discussed above is soil temperature. Sites which have higher average soil temperatures (and subsequent higher mineralisation rates and lower residual mineralisable N pools) are likely to have lower soil moistures. Secondly, the sites which have higher average soil moisture values (southerly and flat sites), are likely to have higher levels of organic matter (see Chapter 4) which in turn leads to a higher mineralisable N value (Sierra, 1996).

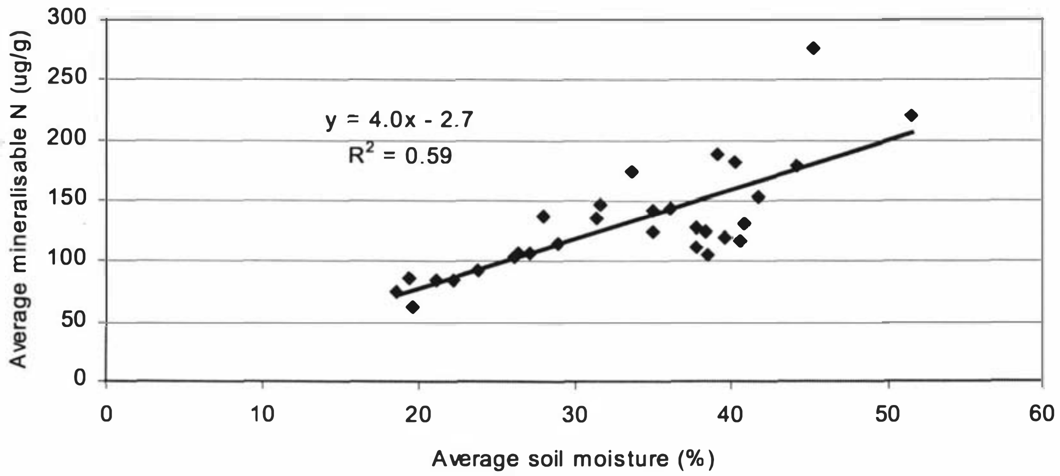


Figure 5.12 Graph of average soil moisture vs. average mineralisable N values (0 – 75mm depth) for each replicate over the period of the trial.

There was a close linear relationship (Figure 5.13) between soil total N (see Chapter 4) and soil mineralisable N ($R^2 = 0.80$). This is largely to be expected, as nearly all the N in soil is present in organic combination.

The average mineralisable N values for each site do not relate as well with the total P (see Chapter 4) values ($R^2 = 0.36$; data not shown) as with the total N values. However they correlate much better than the Olsen P values ($R = 0.08$; data not shown). The better correlation with the total P soil data is likely to be due to the fact that total P concentrations are related to the total N results (see Chapter 4). The lack of a relationship between mineralisable N and Olsen P reaffirms the suggestion that P fertiliser additions may not provide the expected pasture responses on some sites. This was due to the dry nature of the area inhibiting clover growth, which in turn limited inputs from N fixation and deprived the associated grasses of N.

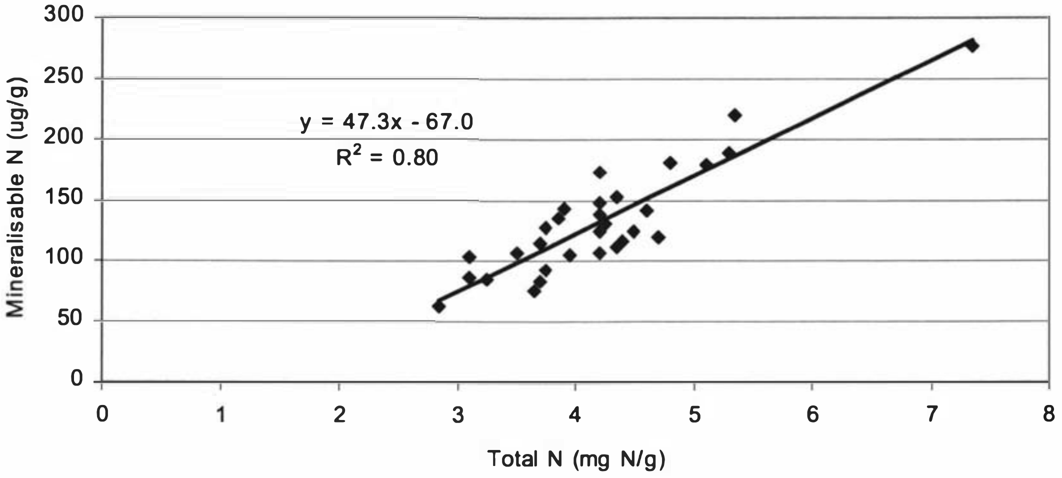


Figure 5.13 Average mineralisable N for each site vs. total N in the top 75 mm.

5.4 CONCLUSIONS

Gravimetric soil water contents varied markedly throughout the year and between the various aspects and slopes - with the southerly aspects being wetter than the flat and northerly aspects at all times of the year. The difference between the aspects is largely caused by the difference in radiation inputs but also by the likely differences in soil moisture holding capacity (not measured). Soil temperatures tended to follow the opposite pattern to the soil moisture, with the northerly aspects having higher temperatures at all times of the year. When radiation inputs increased, soil moistures dropped more on northerly aspects, and temperatures there tended to increase more than the southerly aspects. The radiation input over the year and between the different aspects and slopes is a basic factor modifying micro-climate in hill country as it not only causes variations in the soil but is also a major factor affecting seasonal pasture growth.

The soil ammonium-N and nitrate-N levels proved to be very variable, not only between samplings but also within sites. This variability, caused largely by the dynamic nature of the N system due to large inputs and losses at any given time, and the spatial variability of animal returns which creates N "hot spots" (urine patches), reduces the usefulness of ammonium-N and nitrate-N soil tests as indices of soil nitrogen in grazed pastures. This concern has been shared by many other authors in the past.

The mineralisable N results appeared to provide a much more relevant measure of soil nitrogen. Results were reasonably consistent within sites, and similar patterns were followed by all sites throughout the year. Mineralisable N appeared to correlate well with soil moisture. However, this relationship is not straightforward. The size of the mineralisable N pool will be influenced by the amount of organic N in the soil that potentially can be mineralized. This tends to result in the flat and south-facing slopes having higher mineralisable N levels because biological production is higher on these areas due to higher soil moistures.

At the same time the size of the mineralisable N pool is affected by conditions immediately prior to the soil sample being collected. If conditions prior to sample collection are favourable for mineralisation, then it is likely that the mineralisable N pool will have been depleted prior to measurement in the laboratory. This may be a contributing factor to the lower mineralisable N values found on warm north-facing slopes and after drying periods of warm weather.

The mineralisable N values related well to the total N values, however, there were only poor relationships with total soil P and Olsen P values. This reinforced the conclusion that higher P levels have had little effect on the N concentration in soil due to the lack of clovers and short time period for high P soil levels have been in place.

CHAPTER 6

PASTURE GROWTH DATA

6.1 INTRODUCTION

As discussed in the introduction to Chapter 5, the purpose of this trial was to separate out the effects of environment and soil nutrient supply on pasture growth. This was attempted by creating non-limiting nutrient conditions at each site and comparing pasture growth with that achieved under existing conditions of soil fertility.

This Chapter will discuss the variations in pasture growth between aspects, slopes and soil fertilities throughout the period of one year, and isolate the major factors affecting and limiting pasture growth on individual sites. An attempt will also be made to relate the pasture growth data to the soil tests measured over the period of the trial which were discussed in Chapter 5.

6.2 MATERIALS AND METHODS

Details of the design and operation of the pasture growth trial are presented in Chapter 5.

6.2.1 Herbage dry matter and composition

Once the pasture samples had been collected, a sub-sample was removed and dissected for clover content. All samples were then dried at 35 °C for 2-3 days and weighed. Pasture growth rates were estimated from harvested yields and the length of the respective growth periods (Table 6.1).

Table 6.1 The dates of the 8 pasture growth periods

Sampling	Dates of growth periods
1	3/3/99 – 9/4/99
2	9/4/99 - 11/5/99
3	11/5/99 – 9/7/99
4	9/7/99 – 4/9/99
5	4/9/99 – 12/10/99
6	12/10/99 – 16/11/99
7	16/11/99 – 12/1/00
8	12/1/00 – 28/2/00

6.2.2 Pasture N content

A representative dry portion of pasture was removed from each sample and ground in a herbage grinder. A 0.1000g sample of the pasture was placed in a Pyrex tube with 4ml of Kjeldahl digest mixture (McKenzie and Wallace, 1954) and heated to 350°C for four hours. The solution was then diluted to 50 ml using deionised water and mixed thoroughly in a vortex shaker. The samples were analysed for nitrogen on a Technicon II autoanalyser.

6.3 RESULTS

Although this trial produced a wealth of important data, the presentation of these data in a readily comprehensible format posed something of a challenge. The trial contrasted aspects (north and south), slopes (steep and easy) and P status (high and low). However, the inclusion of flat sites, which provided a contrast of both slope and aspect in a single landscape unit complicated any simple factorial analysis to identify "main effects". In addition, the usefulness of any analysis of main effects was diminished by the very strong interactions between slope and aspect, which often rendered meaningless any averaging of steep (or easy) sites across aspects, or easy and steep sites on the same aspects.

When rate of pasture growth throughout the year is considered, the picture is complicated still further. There were strong seasonal trends evident in the rate of pasture growth, but these trends differed markedly between slopes and aspects. Once again, this made it difficult to simplify data presentation by averaging across sites.

Therefore, in the sections that follow, the complete pasture growth data for all sites and times (where appropriate) are presented in tabular form, followed by a separate Table that identifies contrasts between sites that are statistically significant. Selected contrasts are then discussed with the use of Figures to highlight the comparison under discussion.

A multi-factorial unbalanced analysis of variance was used to statistically analyse the data. In regards to the statistical analysis of seasonal data, comparisons were made only between sites at any one sampling time. No attempt was made to include a "repeated measures model" to assess the statistical significance of changes in pasture growth rate over time. Although such an analysis would have been possible (but complex), it would have added little to the interpretation of the data.

6.3.1 Pasture yields in the absence of added nitrogen

Figure 6.1 shows the total annual pasture production over the period of the trial in the absence of added N fertiliser. The maximum growth was on the HPNE sites which recorded an average annual pasture production of 9067 kg D.M./ha. The lowest growth was recorded on the HPNS sites with an average total production of 2394 kg D.M./ha. There was therefore, a large difference in the amounts of total pasture that were grown over a year, with the highest producing sites producing more than three times as much as the lowest producing sites.

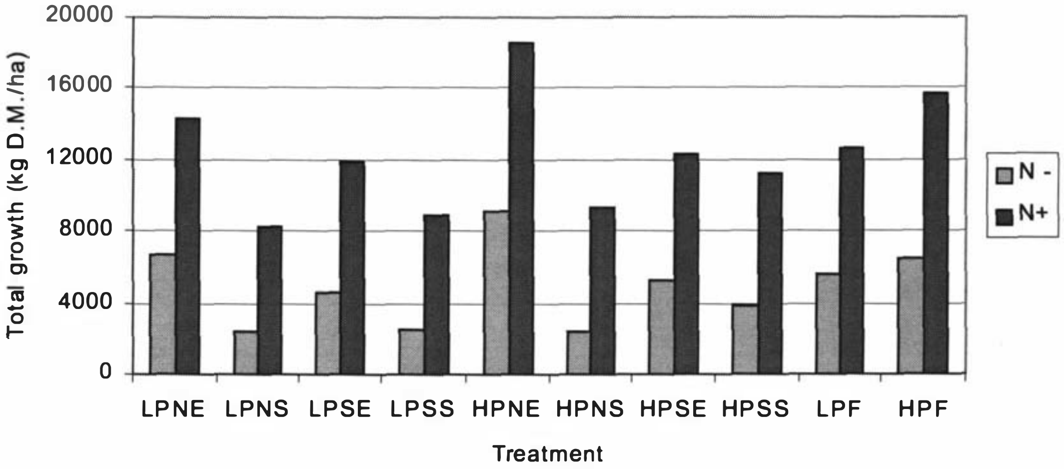


Figure 6.1 Comparison of total growth between nitrogen limited and nitrogen unlimiting plots within each site.

The statistical analysis of the total herbage production data presented in Table 6.2 shows that most of the differences in pasture production between landscape units were highly significant. Because of the unbalanced design and large interactions in total growth between slope and aspect, main effects are hard to display. Nonetheless, some patterns are evident in Figure 6.2.

There was a significant positive effect on total growth from increased P fertility (Table 6.2, Figure 6.2A). All landscape classes except for NS sites, exhibited increased total pasture growth from increased P fertility, with the greatest response recorded on the NE sites.

Flat sites produced significantly more total pasture than any of the southerly or steep sites. There was no overall significant difference between northerly sites and flat sites, as although the NS sites produced significantly less pasture than the flat sites, the effect was balanced out by more growth on the NE sites.

Table 6.2 Statistical analysis of selected contrasts of total pasture growth.

Contrast	**N-limited plots**	**N-added plots**	**Clover**
HP vs. LP	**	**	**
NE vs. NS	**	**	**
NE vs. SE	**	**	**
NE vs. SS	**	**	**
NE vs. F	*	-	**
NS vs. SE	**	*	**
NS vs. SS	-	-	**
NS vs. F	**	**	*
SE vs. SS	*	-	-
SE vs. F	-	-	-
SS vs. F	**	**	-
North vs. South	*	-	*
Easy vs. Steep	**	**	**
North vs. Flat	-	-	**
South vs. Flat	**	**	-
Easy vs. Flat	-	-	**
Steep vs. Flat	**	**	-

* = $P < 0.05$; ** = $P < 0.01$.

The statistical analysis in Table 6.2 indicates that northerly aspects produced significantly more pasture than southerly aspects. However, Figure 6.2B shows that this additional production on northerly aspects occurs solely on easy sites and there was no difference between north- and south-facing steep sites.

There was significantly more total pasture produced on easy slopes compared to steep slopes (Table 6.2) on all treatments, with the greatest differences on LP and HP northerly treatments (Figure 6.2C). The factors affecting pasture growth throughout the year and reasons for the variations within treatments and sampling times will be discussed later in section 6.4.

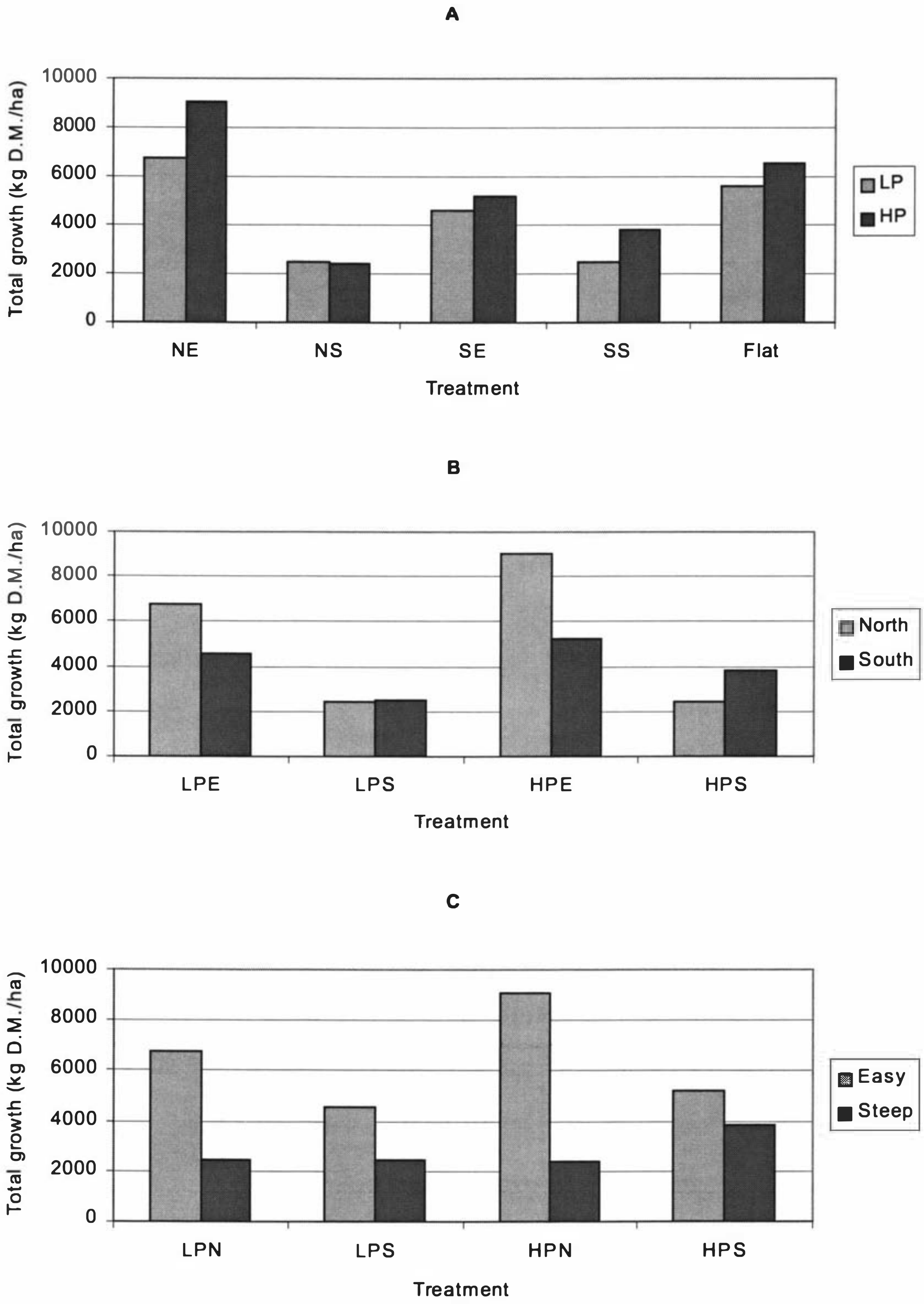


Figure 6.2 Annual pasture production in the absence of added N highlighting some important contrasts. (Note in 6.2B, S = steep; in 6.2C, S = south).

When annual pasture production is broken down into seasonal production the situation becomes even more complex, with large variations in pasture growth within sites over time, and also between sites within a given growth period. Table 6.3 presents the average daily growth rates of pasture, in the absence of added nitrogen, for the 8 growth periods.

Pasture growth rates ranged from 1 kg D.M./ha/day for the LPNS sites in growth period 6 (mid spring) to 34.5 kg D.M./ha/day for the HPSE sites in the same period. The largest difference within a treatment over time throughout the year was 29.8 kg D.M./ha/day (from 4.7 to 34.5 kg D.M./ha/day) for the HPSE sites. The largest variation within a growth period was a difference of 33.4 kg D.M./ha/day (between 1.1 kg D.M./ha/day on the LPNS sites and 34.5 kg D.M./ha/day on the HPSE sites) in growth period 6 (mid spring).

The statistical analysis of the data presented in Table 6.4 reveals some interesting contrasts. It was noted earlier that total annual pasture production was significantly higher on HP sites than on LP sites. Inspection of Figure 6.3 reveals that this increase in production occurred mainly in growth periods 6, 7, 8 and 1 – namely spring and summer. This was verified by the statistical analysis in Table 6.4 that suggests that differences in rates of growth between HP and LP plots were only significant in growth periods 6,7 and 8.

Table 6.3 Daily pasture growth rates of sites in the absence of added N (kg D.M./ha/day) for the 8 growth periods.

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LPNE	18.86	19.36	19.13	20.71	31.02	9.87	17.74	12.55
LPNS	14.03	8.05	8.08	4.57	9.54	1.13	5.86	4.04
LPSE	18.69	7.19	7.46	6.59	18.96	17.00	18.77	9.79
LPSS	12.74	4.82	3.68	3.60	10.49	9.41	10.98	1.48
HPNE	28.84	16.41	21.21	19.56	32.57	28.79	30.47	24.05
HPNS	20.52	4.09	3.57	4.47	4.71	4.62	10.08	#
HPSE	13.92	8.82	8.54	4.72	21.00	34.51	19.98	10.54
HPSS	13.53	12.56	6.41	5.86	13.06	15.55	15.12	5.93
LPF	20.22	14.73	10.45	13.15	18.50	29.10	19.63	3.28
HPF	26.28	16.53	20.58	11.93	24.67	20.29	16.12	11.95

- Samples were lost due to cattle knocking over the cages protecting the pasture growth sites.

Table 6.4 Statistical analysis of selected contrasts of rate of pasture growth between sites in the absence of added N over 8 growth periods.

Contrast	1	2	3	4	5	6	7	8
HP vs. LP	-	-	-	-	-	*	*	**
NE vs. NS	-	**	**	**	**	**	**	*
NE vs. SE	*	**	**	**	*	-	-	-
NE vs. SS	**	**	**	**	**	-	*	*
NE vs. F	-	-	-	-	*	-	-	-
NS vs. SE	-	-	-	-	**	**	**	-
NS vs. SS	-	-	-	-	-	*	-	-
NS vs. F	-	**	**	**	**	**	*	-
SE vs. SS	-	-	-	-	-	**	-	-
SE vs. F	-	**	*	*	-	-	-	-
SS vs. F	**	**	**	**	*	*	-	-
North vs. South	*	**	*	*	-	*	-	-
Easy vs. Steep	-	**	**	**	**	**	**	*
North vs. Flat	-	*	-	-	-	**	-	-
South vs. Flat	**	**	**	**	-	-	-	-
Easy vs. Flat	-	-	-	-	-	-	-	-
Steep vs. Flat	*	**	**	**	**	**	*	-

* = $P < 0.05$; ** = $P < 0.01$.

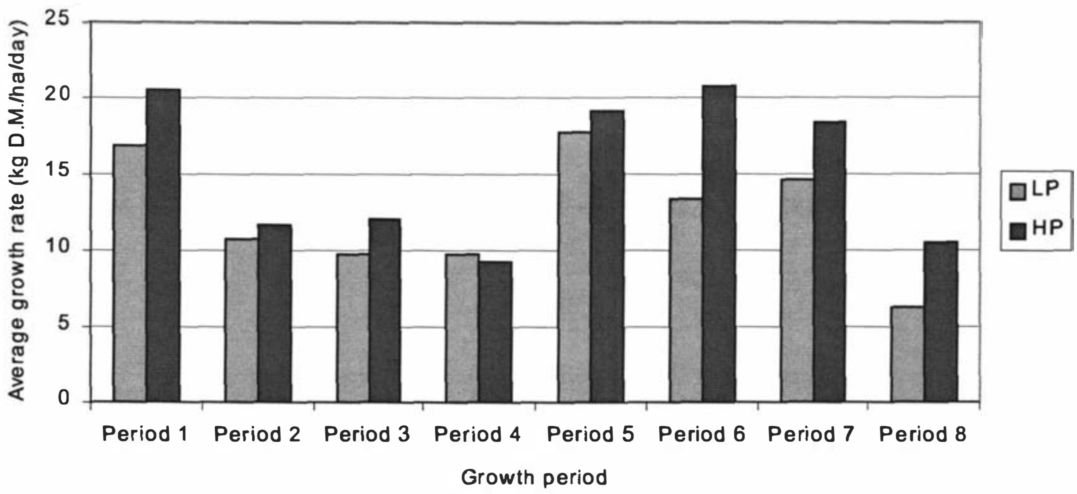


Figure 6.3 Averaged daily growth rates (kg D.M./ha/day) across slopes and aspects showing the effect of soil P status in each growth period for sites in the absence of added N.

If easy and steep sites are averaged together on each aspect to enable a simple comparison of north-facing, south-facing and flat sites then an interesting pattern emerges (Figure 6.4). On average north-facing, and flat sites had higher rates of growth than south-facing sites through autumn, winter and into early spring (growth periods 1-5). For much of that time (growth periods 1-4) these differences are statistically significant (Table 6.4).

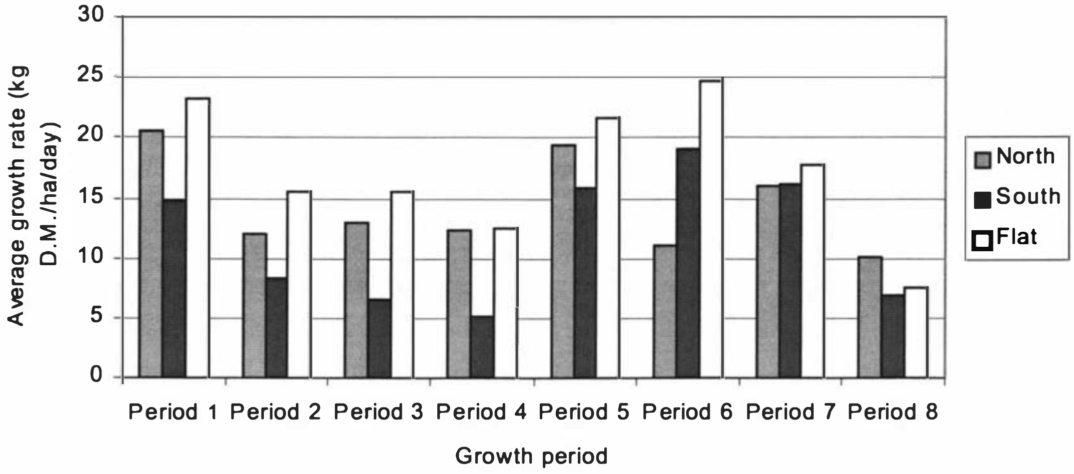
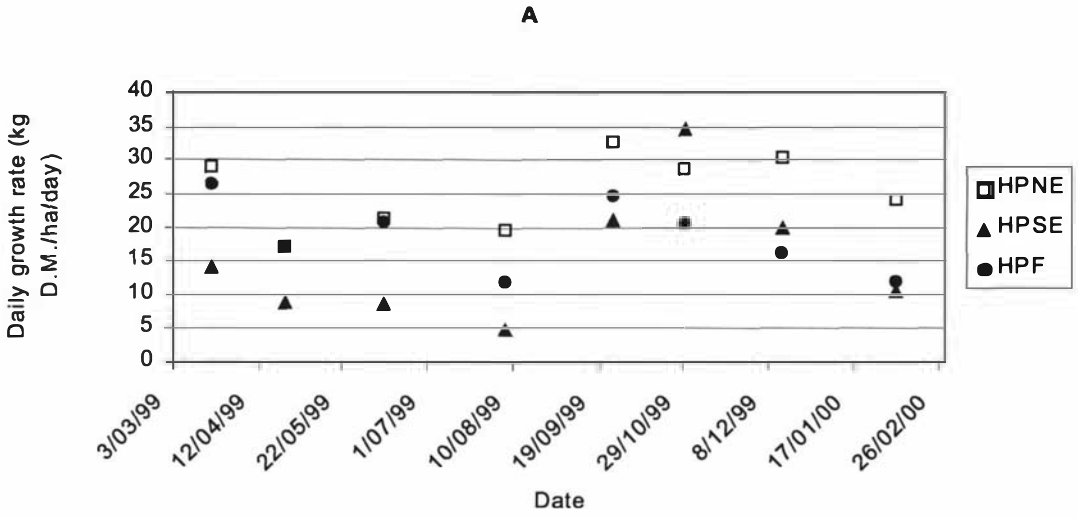


Figure 6.4 Averaged daily growth rates (kg D.M./ha/day) across slopes and P fertilities showing the effect of aspect in each growth period for sites in the absence of added N.

Through late spring and summer, the differences in rate of growth diminished and became non-significant, except in growth period 6 when the situation described above was reversed, and the north-facing slopes (on average) had significantly lower rates of growth than both the flat and south-facing slopes.

Consideration of Figure 6.5A & B however reveals that, although on average, north-facing slopes had higher rates of pasture growth than south-facing slopes through autumn and winter, nearly all of this difference occurred on easy slopes. With the exception of a dry period in late spring/early summer, north-facing easy slopes had considerably higher rates of growth than south-facing easy slopes throughout the year. In contrast, north-facing steep slopes had similar growth rates to their south-facing counterparts in autumn/winter and tended to have lower rates of growth than southerly slopes over spring and summer, when the southerly slopes had higher moisture contents. Figures 6.5A & B do not include the LP treatments which further cloud the variation between the aspects (Table 6.3).

Also of interest is the comparison of HP north-facing and flat slopes. When pasture growth on steep and easy north-facing slopes was averaged there was little difference in rate of growth compared to flat sites. However, inspection of Figure 6.5A & B suggests that in fact, north-facing steep slopes have much lower rates of pasture growth than flat sites throughout the year, but this was compensated for by NE slopes which had higher rates of pasture growth than flat sites in spring and summer.



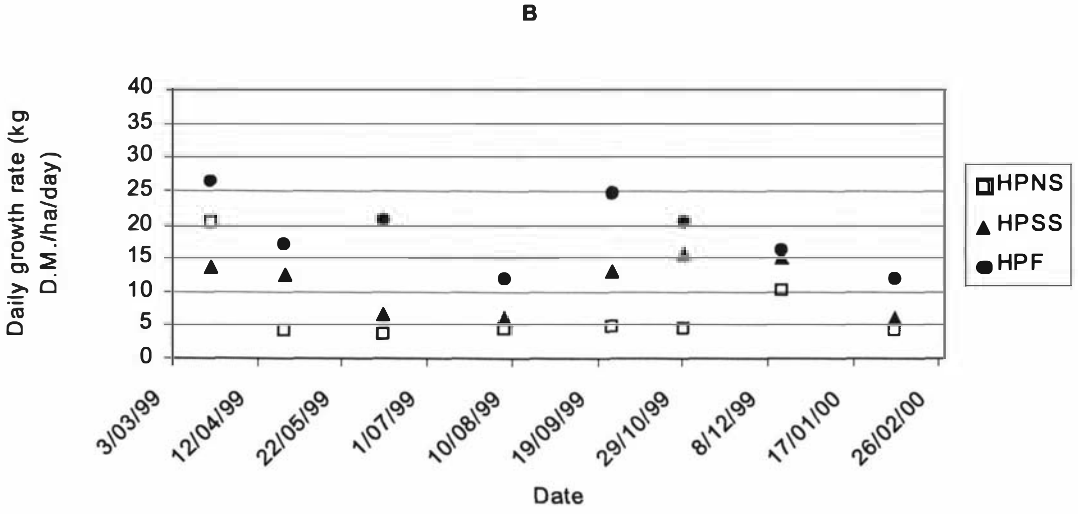


Figure 6.5 Daily pasture growth rates on HP sites in the absence of added N, highlighting the variation between aspects throughout the year.

On average, easy slopes had significantly higher pasture growth rates than did steep slopes, throughout the year, except for growth period 1 at the start of autumn (Figure 6.6; Table 6.4). Once again however, when this "main effect" is analysed in more detail, it is apparent that the effect of slope differed between aspects (Figure 6.7A & B). On northerly aspects, easy slopes outproduced steep slopes throughout the year. In contrast on the southerly aspect, there was little difference in pasture growth rate between easy and steep slopes throughout most of the year, except for spring (growth periods 5 & 6). In growth period 6 particularly, growth rates on southerly easy sites were much higher than on southerly steep sites.

The significantly higher pasture growth rate on flat sites than steep sites throughout the year, except for late summer, is clearly shown in Figures 6.7A & B. The HPF sites produced more pasture than the HPNS and HPSS sites throughout the year but with a much bigger difference between the HPF and HPNS sites. There was no significant difference in pasture growth rate between the easy and flat treatments throughout the year.

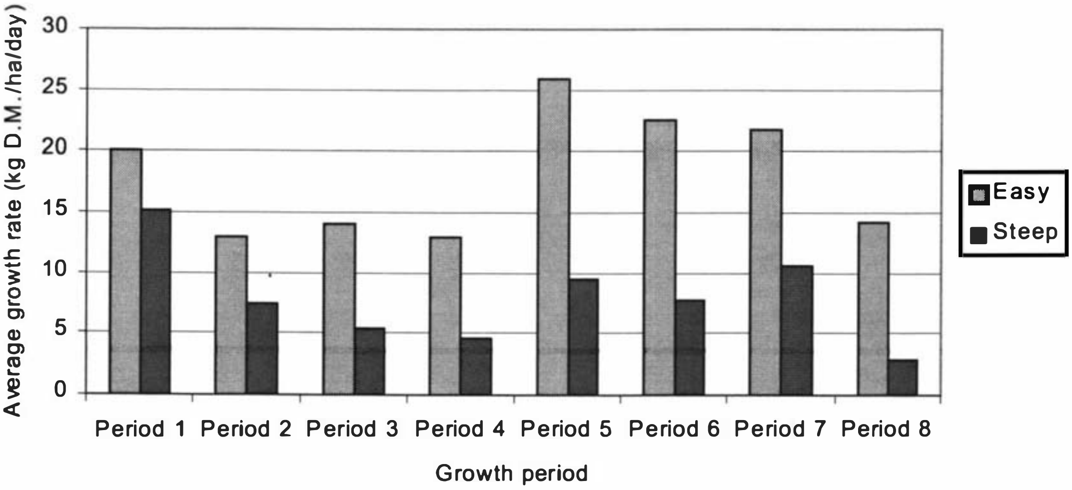


Figure 6.6 Averaged daily pasture growth rates (kg D.M./ha/day) across P fertilities and aspects showing the effect of slope in each growth period for sites in the absence of added N.

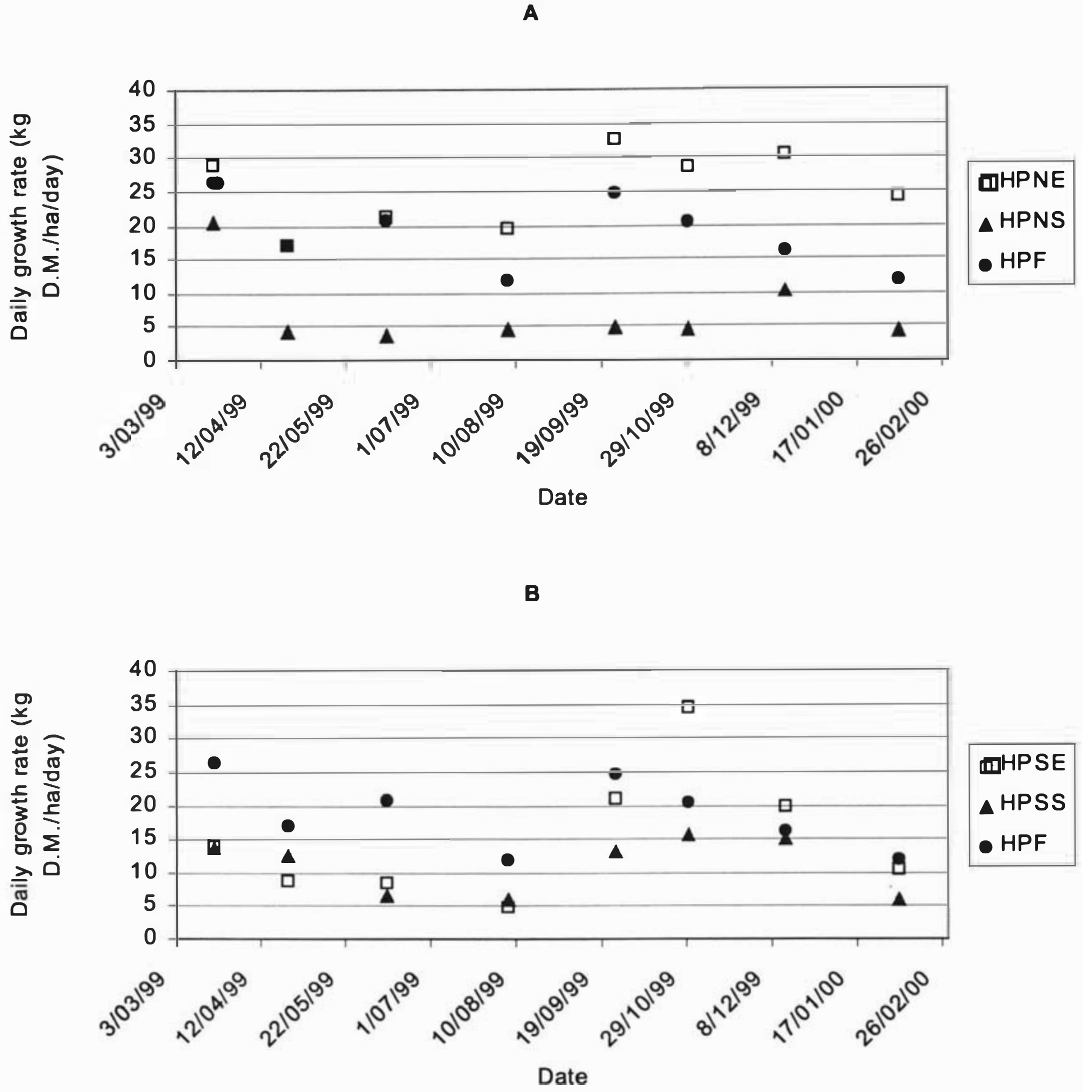


Figure 6.7 Daily pasture growth rates on HP sites in the absence of added N, highlighting the variation between slopes throughout the year.

It is of interest that the lowest and highest growth rates were recorded on contrasting sites in the same growth period, and the largest variation in growth rate at a site over time was recorded at the sites that recorded the highest growth rate. This highlights the fact that in dry hill country, environmental factors that influence pasture growth vary markedly within different slopes and aspects throughout the year. Work by Lambert (1977), and Luscombe (1980) supports these findings. Both studies were carried out on hill country in the Southern Hawkes Bay with similar topography to that of the Waipawa trial, but with a higher rainfall. Lambert (1977) measured pasture growth on north and south aspects throughout the year and values were averaged across slopes ranging from 5 -30°. Taking into account that the measurements were averaged across slopes, the values obtained were similar to those found in this study with a range of 3 - 21 kg D.M./ha/day. Luscombe (1980) measured pasture growth on north-easterly and south-westerly aspects of 10-15° slopes. Growth rates in this study were much higher, ranging from 16-56 kg D.M./ha/day. Radcliffe (1975) investigated pasture growth rate on a site very close to the Waipawa trial at Maraekakaho with a similar climate. The study was carried out on flat ground and on average, pasture growth rates ranged from 11.5 – 33.0 kg D.M./ha/day, similar to the values found on the flat sites in this trial. The pasture growth rates found in this study are therefore, well within expected levels for this type of country.

6.3.2 Pasture growth in the presence of non-limiting nitrogen

The total annual pasture production in the presence of unlimited N is shown in Figure 6.1. Annual production at all sites was much higher than in the absence of added N. As was the case in the absence of added N, the highest annual dry matter production was recorded on the HPNE sites which grew an average of 18532 kg D.M./ha/yr, whilst the lowest dry matter production value was recorded on the LPNS sites which produced 8001 kg D.M./ha/yr.

Statistical analysis of the data (Table 6.2) reveals a similar pattern of significant differences in pasture growth to that in the absence of added nitrogen. Figure 6.8 highlights some of the statistically significant differences in total growth between the various sites.

As indicated earlier, pasture production is normally constrained by both climatic and soil fertility factors. The purpose of adding high rates of N (particularly on the high P sites) was to assess potential pasture production in the presence of non-limiting soil fertility (P & N) and to identify the variation in climatic constraints between sites. The fact that under these conditions there was still a difference of 10531 kg D.M./ha between the highest and lowest producing sites (compared to a difference of 6673 kg D.M./ha in the absence of added N) highlights the importance of topography and associated micro-climates in regulating annual pasture production. This difference exists independent of soil fertility.

It is interesting to note that even in the presence of unlimiting N, HP status still had a significant positive effect on total pasture growth (Table 6.2). The effect of P status was not uniform across the trial however, with little or no response on NS and SE sites (Figure 6.8A). Further discussion of the effect of P fertility on pasture growth will occur later in the chapter. Figure 6.8A also highlights that significantly more pasture was grown on flat sites than on both southerly and steep sites (Table 6.2).

Unlike the total pasture growth on sites in the absence of added N, there was no significant difference between the north and south aspects in total pasture production with unlimited N (Table 6.2). Figure 6.8B shows that the northerly aspects produced more pasture in the LP easy and HP easy treatments, however the southerly aspects produced more pasture than the northerly aspects in the LP steep and HP steep treatments. When these data are compared with sites in the absence of added N (Figure 6.2B) the major difference between the two sets of data is that the relative difference between NE and SE sites is reduced in the presence of non-limiting N. The difference in total pasture production between north and south aspects in the presence of non-limiting N, is therefore reduced and was not statistically significant (Table 6.2). Further discussion on possible reasons for the diminished effect of aspect will be discussed later in terms of seasonal production.

Easy sites produced significantly more total annual pasture than steep sites (Figure 6.8C; Table 6.2). As for sites in the absence of added N, the difference between easy and steep sites was much less for the HP south sites, than other sites. This effect was largely due to HPSS sites producing more total annual pasture than the other steep sites, which all produced similar amounts. Possible reasons for these variations will be discussed later in section 6.4.

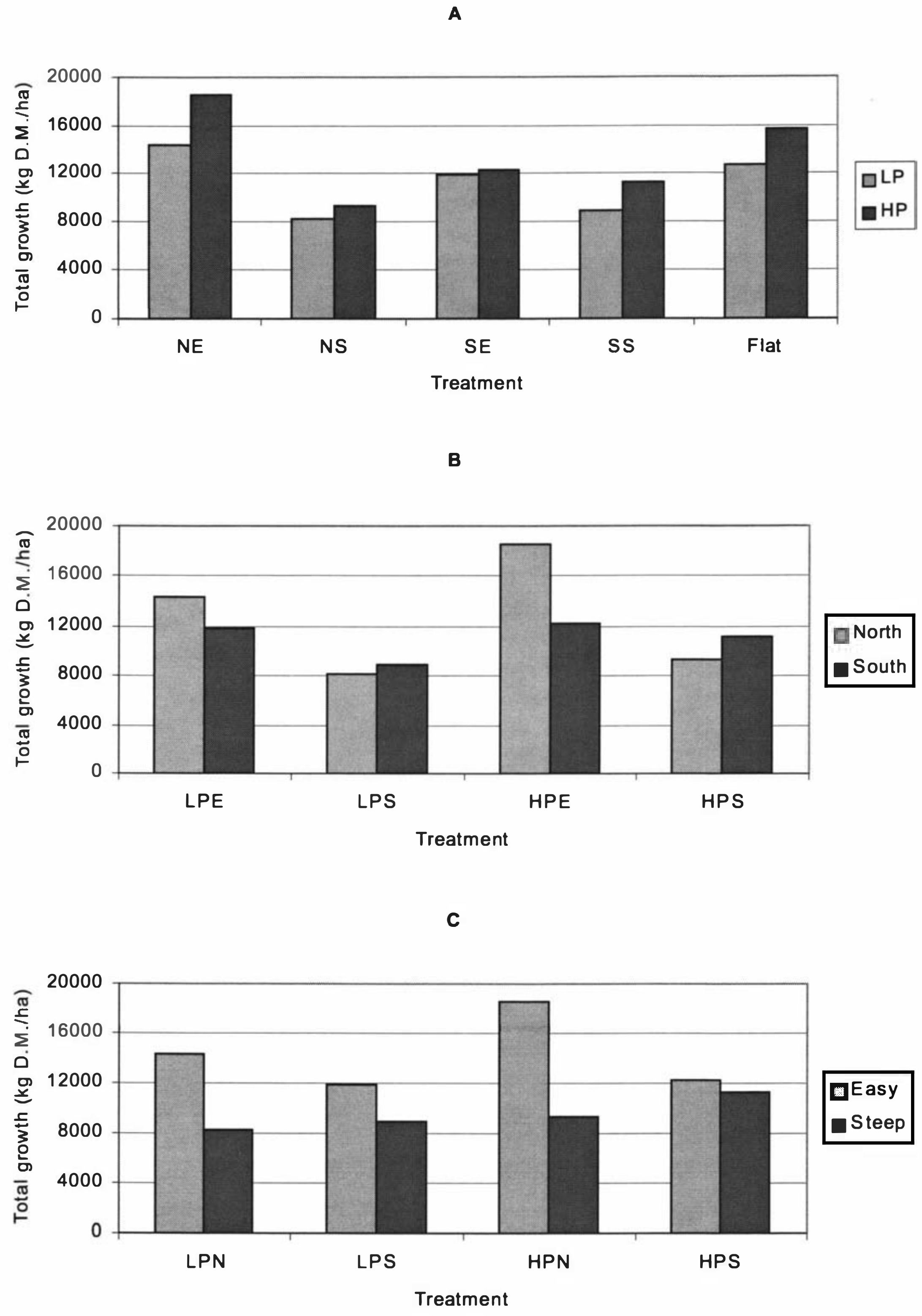


Figure 6.8 Total annual pasture production in the presence of non-limiting N, highlighting some important contrasts. (Note in 6.8B S = steep; in 6.8C S = south).

As was the case in the absence of added N, when annual pasture production is broken down into seasonal production the situation becomes more complex, with large variations in pasture growth within sites throughout the year and between sites within growth periods. The results in Table 6.5 show the average daily growth rates of the plus-N plots throughout the year. Values range from 3.8 kg D.M./ha/day for the LPNS site in growth period 6 in mid spring, to 78.0 kg D.M./ha/day for the HPNE sites in growth period 5 in early spring. The largest variation within a site over time is 44.3 kg D.M./ha/day for the HPSE site, whilst the largest variation between sites within a growth period was 57.5 kg D.M./ha/day for growth period 5 (early spring). The comparable maximum ranges in pasture growth rates in the absence of added N (Section 6.3.1) were 29.8 kg D.M./ha/day within a site over time, and 33.4 kg D.M./ha/day between sites at any one sampling.

Thus there were larger variations in pasture growth rates between sites within a growth period and also within a site over time on sites receiving non-limiting N than was observed on N limited sites. This indicates that when nutrient restrictions are removed, the variation in climatic restrictions on pasture growth between sites is exaggerated further. In other words, nutrient supply as it affects pasture growth is more uniform across the hill country landscape than the climatic determinants of plant growth.

Table 6.5 Daily pasture growth rates of sites in the presence of non-limiting N (kg D.M./ha/day) for the 8 growth periods.

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LPNE	45.83	38.11	35.94	32.69	69.07	19.33	59.00	15.98
LPNS	38.39	26.44	29.42	32.13	20.50	3.78	18.77	8.32
LPSE	37.97	15.19	15.75	21.08	53.58	54.71	50.66	21.00
LPSS	37.90	18.50	8.70	10.49	38.86	44.53	44.31	5.78
HPNE	55.01	46.11	41.05	42.73	77.95	44.66	65.28	40.70
HPNS	37.58	22.85	34.06	30.57	21.13	8.30	41.59	#
HPSE	43.09	26.88	15.91	13.85	54.41	58.14	49.69	23.61
HPSS	44.56	20.71	12.90	14.78	51.40	40.05	47.80	24.43
LPF	52.37	22.97	21.95	29.32	51.65	52.90	46.42	12.63
HPF	59.69	31.27	31.28	28.33	60.23	58.73	60.26	27.03

- Samples were lost due to cattle knocking over the cages protecting the pasture growth sites.

Table 6.6 Statistical analysis of selected contrasts of rate of pasture growth between sites in the presence of non-limiting N over 8 growth periods.

Contrast	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
HP vs. LP	-	-	**	-	-	-	-	**
NE vs. NS	*	**	*	-	**	**	**	**
NE vs. SE	-	**	**	**	**	**	-	-
NE vs. SS	-	**	**	**	**	-	-	*
NE vs. F	-	**	**	-	*	**	-	-
NS vs. SE	-	-	**	*	**	**	*	**
NS vs. SS	-	-	**	**	**	**	-	-
NS vs. F	**	-	-	-	**	**	*	*
SE vs. SS	-	-	-	-	-	-	-	-
SE vs. F	*	-	**	-	-	-	-	-
SS vs. F	*	-	**	**	-	-	-	-
North vs. South	-	**	**	**	-	**	-	-
Easy vs. Steep	-	**	**	-	**	**	*	**
North vs. Flat	*	-	**	-	-	**	-	-
South vs. Flat	**	-	**	**	-	-	-	-
Easy vs. Flat	*	-	-	-	-	-	-	-
Steep vs. Flat	**	-	*	-	**	**	-	*

* = $P < 0.05$; ** = $P < 0.01$.

Overall, there is a more consistent P response in pasture growth rates on sites in the presence of non-limiting N than on sites in the absence of added N (Figures 6.9 & 6.3 respectively). However, as was the case in the absence of added N, statistical analysis (Table 6.6) shows that P only has a statistically significant effect on pasture growth rate in periods 3 (early winter) and 8 (late summer).

Examination of Table 6.5 shows that in the presence of non-limiting N, the NE and flat sites produced the largest and most consistent P responses. These NE and flat sites also produced the largest pasture growth rates in the presence of non-limiting N throughout most of the year. Thus the largest P responses occurred on sites with the highest pasture growth rates, suggesting that P was becoming more of a limiting factor to pasture growth when growth rates were higher. This dependence of P response on overall pasture growth rate may also explain the apparently (although not statistically significant) greater P response that occurred in the presence of non-limiting N.

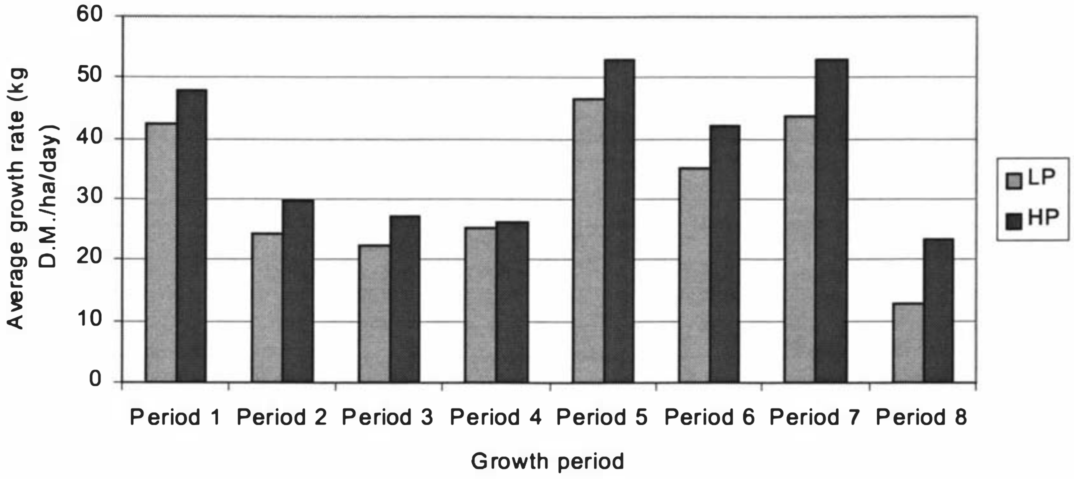


Figure 6.9 Daily pasture growth rates in the presence of non-limiting N (kg D.M./ha/day) averaged across slopes and aspects showing the effect of P fertility in each growth period.

Figure 6.10 highlights the contrast between north and south aspects. The northerly aspects had significantly higher growth rates in autumn and winter (periods 2, 3 and 4) but the reverse was the case in late spring (growth period 6).

Once again however, when easy and steep sites are considered separately, a slightly different picture emerges (Figure 6.11A & B). Except for the dry spell in growth period 6, northerly easy slopes had higher growth rates than their southerly counterparts throughout the whole year. In contrast, northerly steep sites outproduced southerly steep sites only during winter. In summer and autumn there was little difference in growth rates between steep sites in southerly and northerly aspects and in spring the growth rates on the southerly steep sites were considerably higher than on the northerly sites.

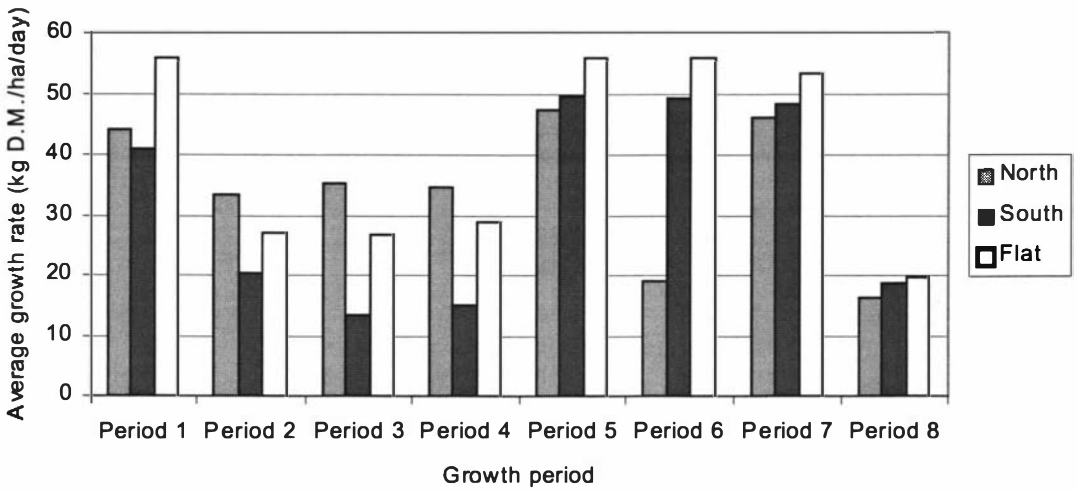


Figure 6.10 Daily pasture growth rates of sites in the presence of unlimiting N (kg D.M./ha/day) averaged across slopes and P fertilities showing the effect of aspect in each growth period.

Overall, it appears that growth rates on northerly aspects were similar to those on flat sites, except during late spring (growth period 6) when production on north-facing slopes was very much reduced (Figure 6.10). When broken down according to slope (Figure 6.11A &B) however, it appears that NE sites had slightly higher growth rates than flat sites throughout much of the year whereas growth rates on NS sites were very much less than on flat sites throughout late spring and summer.

Figures 6.10, 6.11A & B illustrate the difference between the flat and southerly sites with flat sites having significantly higher pasture growth rates (Table 6.6) than on southerly sites in growth periods 1, 3 and 4.

When average pasture growth rates on north and south aspects throughout the year are compared in the presence (Figure 6.10) and absence (Figure 6.4) of non-limiting N, an interesting pattern emerges.

In the presence of non-limiting N, the southerly aspects have higher pasture growth rates relative to northerly aspects when compared with sites in the absence of added N in growth periods 1, 5, 6 and 8. Tables 6.3 and 6.5 show that a large percentage of the increase in pasture growth rates on the southerly aspects relative to the northerly aspects in the presence of unlimiting N in growth periods 1, 5, 6 and 8 occurred through increased pasture growth rates on the SE sites relative to the NE sites. This suggests that in those growth periods, the SE sites in the absence of added N, had a greater restriction on pasture growth imposed on them by N limitations than did NE sites. This restriction was overcome in the presence of non-limiting N and the pasture growth rates on SE sites was then, mainly restricted by climatic factors. It may therefore, be assumed that in those particular growth periods (1, 5, 6 & 8), a soil factor (such as temperature) allowed the NE sites in the absence of added N to provide pasture with more N for growth than SE sites.

Examination of the soil temperatures throughout the period of the trial (Figure 5.2) shows that the greatest difference in soil temperature between the NE and SE sites occurred during growth periods 1, 5, 6 and 8 (if winter is not considered, due to temperature being the major limiting factor on pasture growth on southerly aspects, rather than the supply of nutrients). Therefore, the higher soil temperature on the NE sites in periods 1, 5, 6 and 8, in comparison to the SE sites was likely to have allowed the NE sites to have higher N mineralisation rates. Therefore, in the absence of added N, pasture growth on SE sites was more restricted by N deficiency than on NE sites in those periods, which increased the relative difference in pasture growth rates between north and south aspects. This emphasises the absolute importance of soil temperature in determining the amount of N that is available for pasture growth and explains why there is not a statistically significant difference in total annual pasture yield between north and south aspects in the presence of non-limiting N which is observed in the absence of added N (Table 6.2).

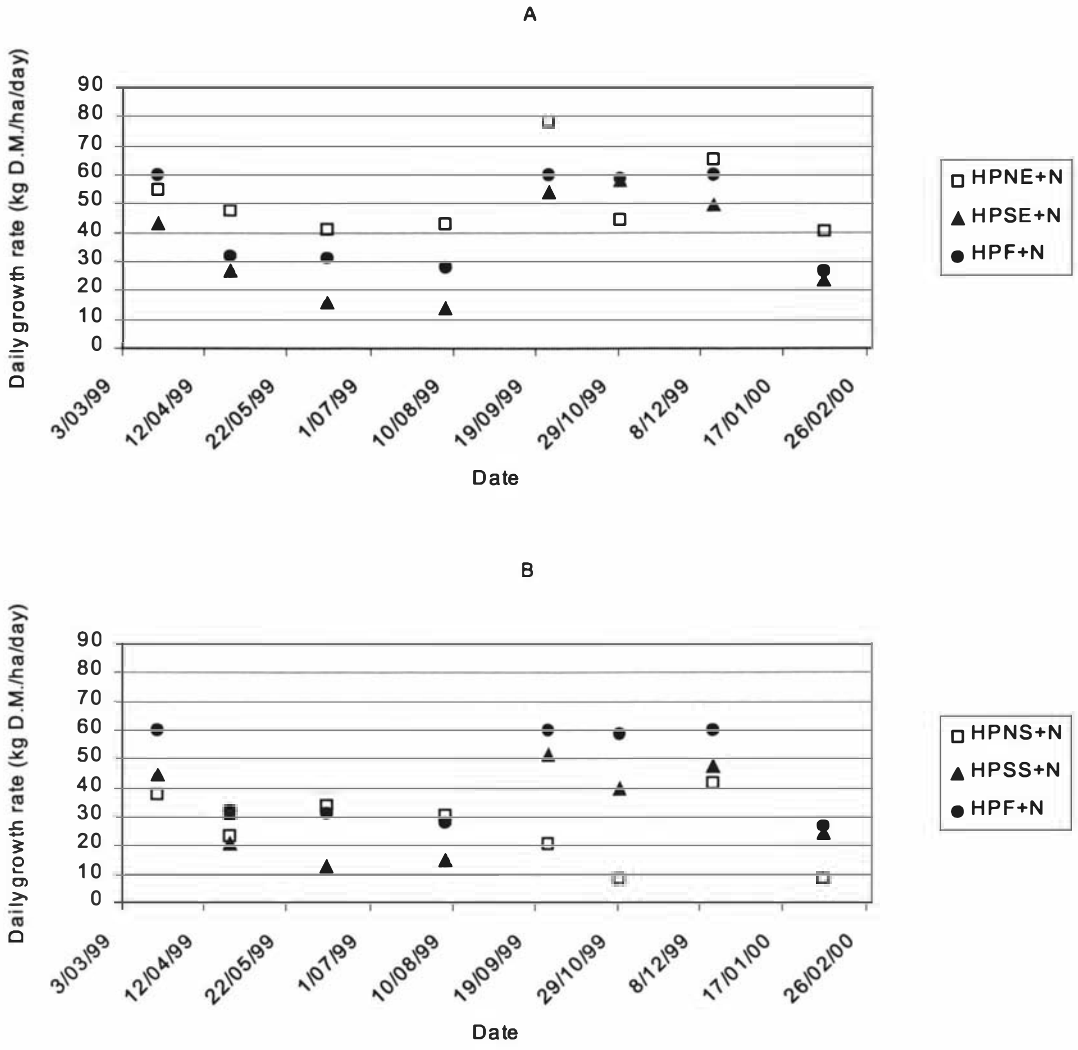


Figure 6.11 Daily pasture growth rates on individual HP treatments highlighting the variation between aspects throughout the year.

When analysed statistically as a main effect, easy slopes had significantly higher pasture growth rates than steep sites in all periods except 1 and 4 (Table 6.6). Figure 6.12 highlights this point when growth rates are averaged across aspects and P fertilities. The difference between easy and steep slopes was much less in the first four growth periods (autumn and winter) than in the last four growth periods (spring and summer).

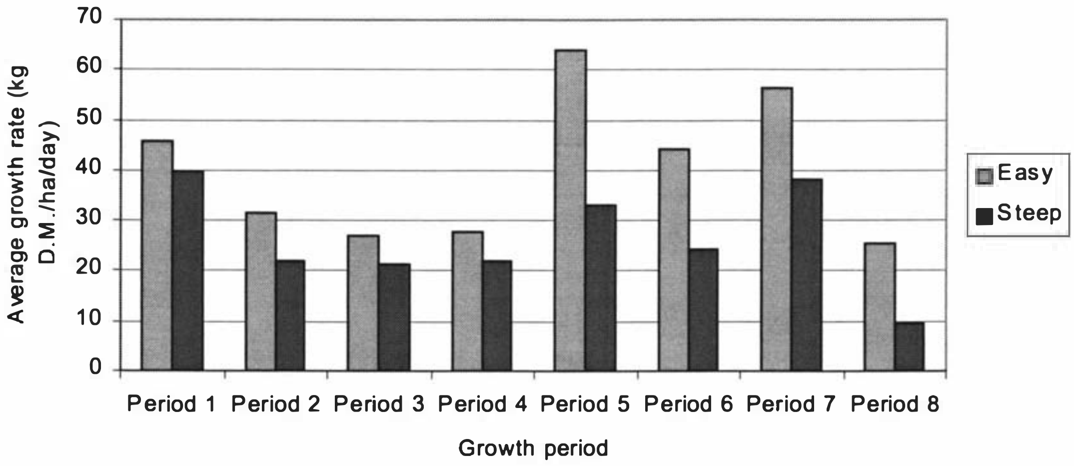


Figure 6.12 Daily pasture growth rates (kg D.M./ha/day) averaged across P fertilities and aspects showing the effect of slope in each growth period.

When easy and steep slopes are compared on each aspect separately (Figure 6.13A & B) it is apparent that most of the increased growth rates on easy slopes compared to steep slopes occurred on the northerly aspect, where the difference was very large. In contrast there was little difference in growth rates between steep and easy sites on the south-facing slopes throughout the year.

The differential in pasture growth rates between easy and steep slopes in the presence of non-limiting N followed much the same pattern throughout the year as sites in the absence of added N except for periods 3 and 4 (winter) (Figures 6.12 & 6.6 respectively). The reduced differential in pasture growth rates between easy and steep slopes in the presence of non-limiting N was due to the higher relative growth rates of the NS sites over the winter, which was not present in the absence of added N.

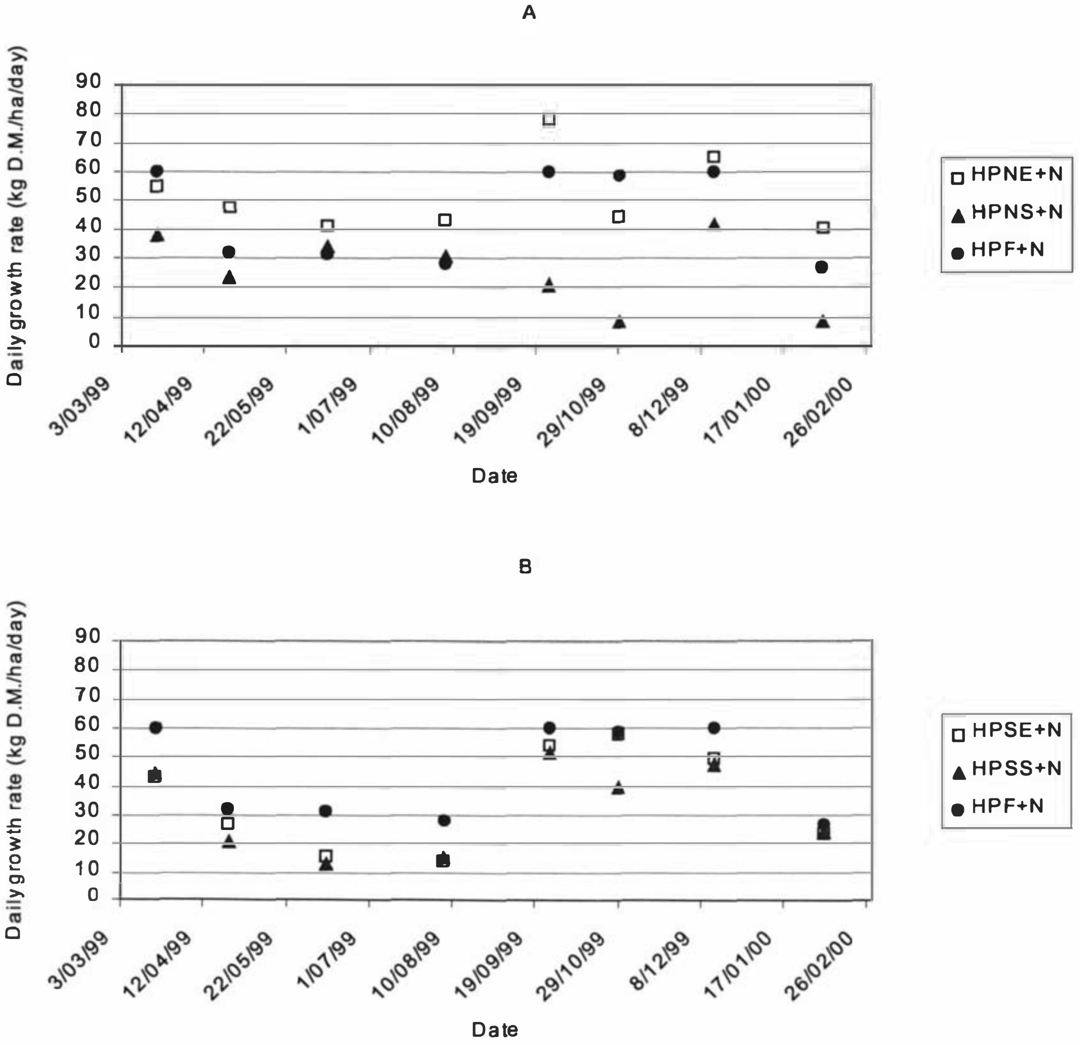


Figure 6.13 Daily pasture growth rates of individual HP treatments highlighting the variation between slopes throughout the year.

There have been many studies investigating pasture growth in relation to N fertiliser application. However it is difficult to draw a direct comparison with growth rates recorded in those studies due to varying rates of N fertiliser used and the contrasting types of country that the studies have been carried out on. However, studies by Ball *et al.* (1978), Luscombe (1980), Ledgard *et al.* (1983) and Lambert and Clark (1986) investigated pasture growth in relation to N fertiliser use on hill country of similar topography, with higher mean rainfalls. Fertiliser rates in these studies ranged from 37 – 448 kg N/ha/yr. Recorded growth rates ranged from 13.2 –118 kg D.M./ha/day. In some of the studies however, growth rates were averaged across slopes and aspects. Growth rates at individual sites may therefore, have been outside the values mentioned above. Considering this, the range of pasture growth rates recorded in this study are well within the range of values recorded in other studies.

6.3.3 Pasture yield limitation due to N deficiency

Traditionally, application of N is measured in terms of a response over and above the pasture grown in the absence of added fertiliser N. This experiment however, allowed an alternative view of this process.

The rate of N added was sufficiently high to enable pasture growth to be unlimited by nutrient constraint. This represents potential yield. In this situation, rather than considering a N response, the difference in growth rate between N unlimiting (potential) and N limited plots can be seen as the extent of depression or limitation of yield (relative to potential) due to N deficiency in the existing pasture.

The limitation in annual pasture yield was relatively even between the sites (Figure 6.14). The highest pasture yield limitations were recorded on the HPNE and HPF sites, which had limitations of 9465 and 9139 kg D.M./ha/yr. respectively, whilst the lowest value was recorded on the LPNS sites at 5757 kg D.M./ha/yr.

The lack of a statistical difference in the extent of limitation in annual pasture yield between the LP and HP sites (data not shown) would tend to suggest that P did not have an effect on the pasture yield limitation. However, the limitation in annual pasture yield was larger on all HP sites than the LP counterparts except for SE sites (Figure 6.14), reflecting the increased P response observed on non-limiting N sites in the previous section. Further discussion on this point will be made later in the Chapter.

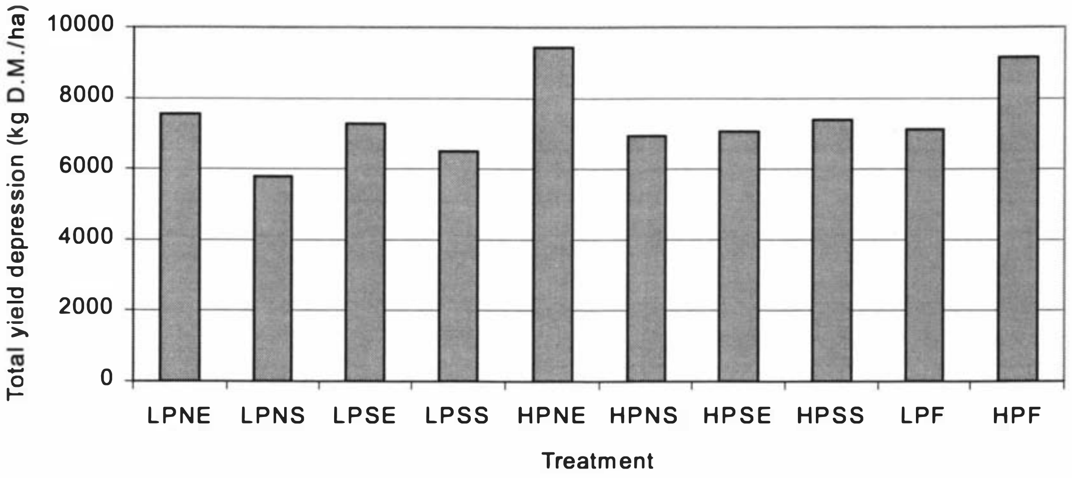


Figure 6.14 Limitation in annual pasture production due to N deficiency for all sites.

The limitations in pasture growth rates due to N deficiency for all sites in each growth period are presented in Table 6.7 and Figures 6.15, 6.16, 6.17 and 6.18. The greatest limitation in growth rate was 45.4 kg D.M./ha/day recorded on the HPNE site in growth period 5 (early spring). The smallest limitation in growth rates was 2.7 kg D.M./ha/day on the LPNS site in growth period 6 (mid spring). The existence of an apparent limitation in pasture growth rates on all sites, at all times of the year (even when pasture growth rates are low), indicates that the soil is unable to supply pasture with sufficient N to reach potential production levels on any site throughout the year. A similar conclusion has been drawn by many authors previously on hill country pastures (Luscombe, 1980; Ball *et al.*, 1982; Ledgard *et al.*, 1983; Chapman and MacFarlane, 1985; Lambert and Clark, 1986).

Table 6.7 Limitation of pasture growth rate due to N deficiency (kg D.M./ha/day) over the 8 sample periods.

Period	1	2	3	4	5	6	7	8
LPNE	26.97	18.75	16.81	22.13	38.05	9.46	41.26	3.42
LPNS	24.36	18.40	21.33	27.55	10.96	2.65	12.91	4.29
LPSE	19.28	8.00	8.29	14.49	34.62	37.71	31.89	11.21
LPSS	25.16	13.68	5.02	6.88	28.37	35.13	33.33	4.30
HPNE	26.17	29.69	19.85	23.18	45.38	15.87	34.81	16.66
HPNS	17.06	18.76	30.48	26.10	16.43	3.69	31.51	#
HPSE	29.17	18.06	7.37	9.13	33.41	23.63	29.71	13.07
HPSS	31.03	8.15	6.49	8.92	38.34	24.50	32.68	18.50
LPF	32.15	8.25	11.49	16.17	33.14	23.79	26.79	9.34
HPF	33.41	14.74	10.69	16.39	35.55	38.44	44.15	15.08

- Samples were lost due to cattle knocking over the cages protecting the pasture growth sites.

Table 6.8 Statistical analysis of the extent of limitation in pasture yield due to N deficiency for the 8 growth periods.

Contrast	1	2	3	4	5	6	7	8
Phosphate	-	-	-	-	-	-	-	*
NE vs. NS	-	-	*	-	**	-	-	*
NE vs. SE	-	*	**	*	-	*	-	-
NE vs. SS	-	*	**	**	-	*	-	-
NE vs. F	-	*	*	-	-	*	-	-
NS vs. SE	-	-	**	**	**	**	-	-
NS vs. SS	-	-	**	**	**	**	-	-
NS vs. F	*	-	**	*	**	**	-	*
SE vs. SS	-	-	-	-	-	-	-	-
SE vs. F	-	-	-	-	-	-	-	-
SS vs. F	-	-	-	-	-	-	-	-
North vs. South	-	*	**	**	-	**	-	-
Easy vs. Steep	-	-	-	-	**	-	-	-
North vs. Flat	*	*	**	-	-	**	-	-
South vs. Flat	-	-	-	-	-	-	-	-
Easy vs. Flat	-	-	-	-	-	-	-	-
Steep vs. Flat	-	-	-	-	*	*	-	-

* = $P < 0.05$; ** = $P < 0.01$.

The data on the limitations on pasture growth rates caused by N deficiency have been divided into the four approximate seasons of autumn (Figure 6.15), winter (Figure 6.16), spring (Figure 6.17) and summer (Figure 6.18) that the 8 growth periods fall into.

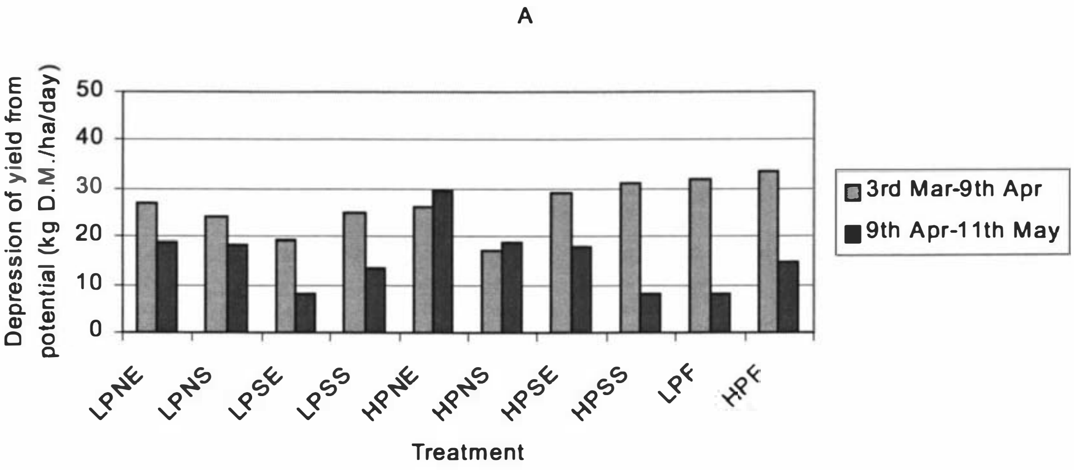
The results for the autumn period (Figure 6.15A) show that at the start of autumn (growth period 1) the limitation of pasture growth rate was relatively even across all sites except for the HPNS and LPSE sites which were less severely restricted. The greatest limitation to growth of 33.4 kg D.M./ha/day occurred on the HPF site. The relative evenness of the response is supported by the statistical analysis data in Table 6.8, which shows no major significant contrasts.

As the trial moved into mid autumn (growth period 2) the N limitation on pasture yield across all sites was reduced, with the exception of the HPN sites. The limitation to pasture yield on the northerly sites was significantly greater than on the southerly and flat sites (Table 6.8).

The magnitude of these differences in growth rate between the +N and –N treatments depends on both N availability, and also the climatic conditions that govern potential growth rate. Thus, in extremely cold or dry conditions, when pasture growth rates are greatly curtailed, the size of any growth response to added N is also likely to be small.

In Figure 6.15A for example, the reduced responses to added N during growth period 2 could either have been due to increased availability of soil N, or a reduced potential growth rate due to less favourable conditions. In an attempt to isolate these two effects, Figures 6.15B, 6.16B, 6.17B & 6.18B present the depression in yield in the absence of added N as a percentage of the potential growth rate measured in the presence of unlimiting N. Results expressed in this way should emphasise the adequacy, or otherwise, of the soil N supply to achieve potential growth.

Thus, by comparing Figures 6.15A and B it is apparent that although the actual measured restriction in growth rate (compared with potential), was very much smaller on most sites in growth period 2, than in growth period 1 (Figure 6.15A), as a percentage of potential growth rate, the restrictions are similar in both growth periods (Figure 6.15B). This suggests that the apparently reduced N deficiency in late autumn was a result of reduced potential growth rates – rather than any increase in the supply of soil N



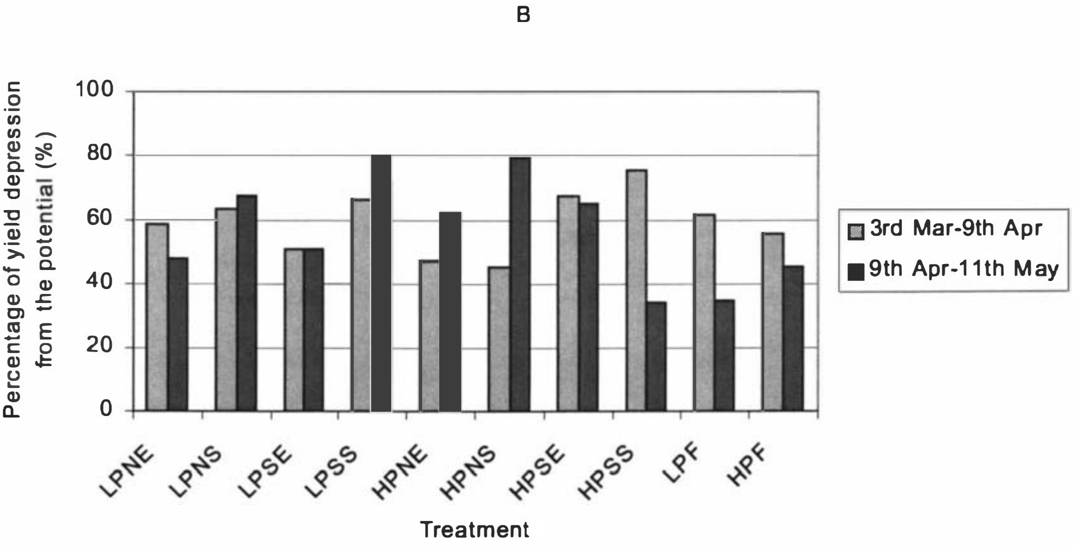


Figure 6.15 Pasture yield limitation for all sites displayed as a quantitative value (A) and a percentage (B) for the autumn period.

Throughout late autumn and early winter (Figure 6.16A, growth period 3) the limitations imposed on pasture growth rates by soil N supply were much greater on northerly sites than on southerly and flat sites. A similar pattern was evident in late winter (growth period 4).

Statistical analysis shows that throughout this period there were significant differences between north and south aspects. In growth period 4 the results (Table 6.7) suggest that there should also be a significant difference between the northerly and flat treatments. However, outlying replicates in both flat sites disrupted the analysis.

When the decreases in pasture growth on the –N treatments are expressed as a percentage of the potential growth rates (Figure 6.16B), then the sites are more even, suggesting that the increased N responses observed on the northerly sites largely reflect better growing conditions.

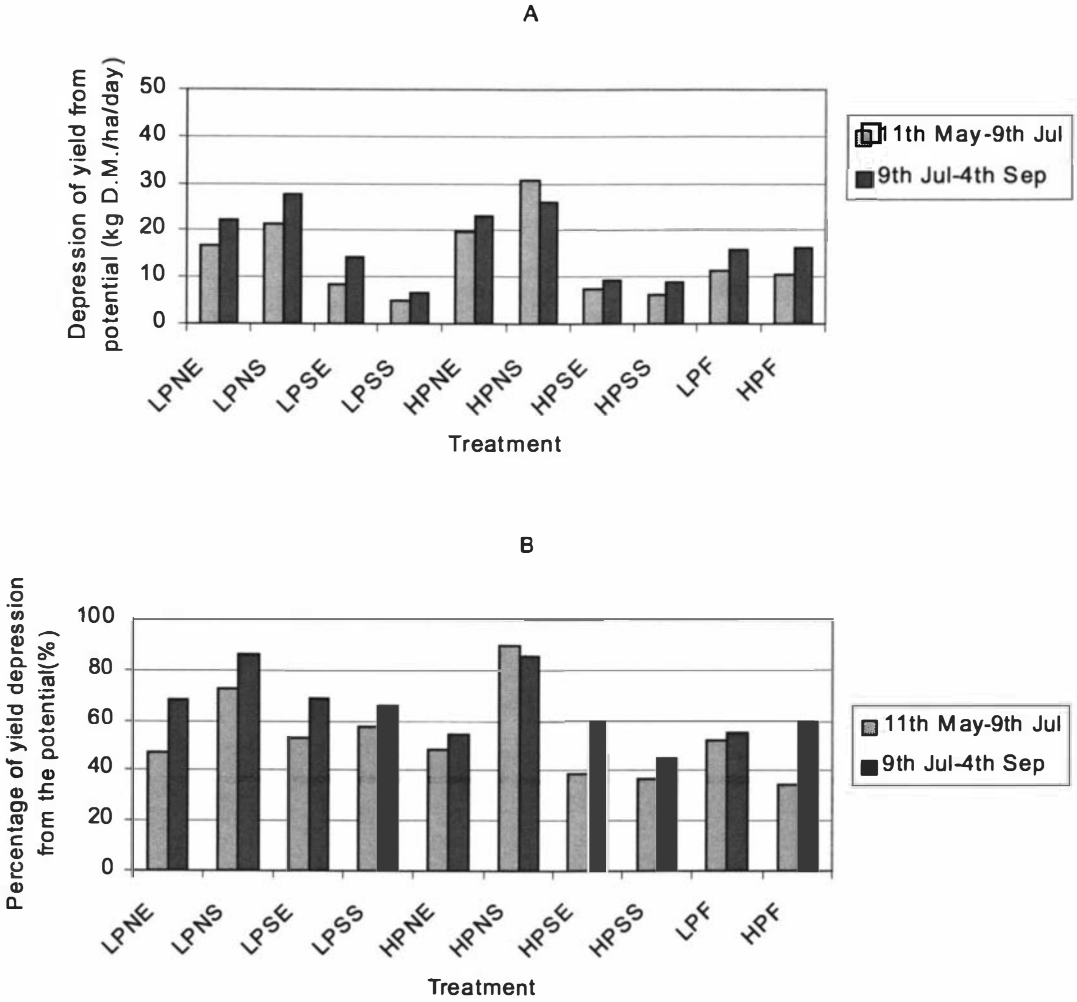


Figure 6.16 Pasture yield limitation for all sites displayed as a quantitative value (A) and a percentage (B) for the winter period.

The advent of spring (Figure 6.17A, growth period 5), resulted in a large increase in the extent to which pasture growth was limited by N deficiency – or, in other words, the extent of the response to added N. The exceptions are the northerly steep sites, which had a reduced pasture yield depression. Statistical analysis (Table 6.8) shows that the NS sites had a significantly lower pasture yield depression than all other sites for growth period 5, when in the previous two periods it had provided the largest pasture yield depressions. The results also show that there was no significant difference between the north and south aspects and for the first time the easy and flat sites had significantly higher restrictions on pasture growth because of N deficiency than the steep sites.

At the end of spring (growth period 6) there was a significant change in the pattern of pasture yield restriction. The difference in pasture growth rates between +N plots on all north-facing slopes decreased markedly, but addition of N fertiliser continued to provide large N responses on the southerly and flat sites.

The small increases in pasture growth rate following N addition on NS sites in early spring, and all northerly sites in mid to late spring, appears to be mostly attributable to less favourable climatic conditions (Figure 6.17B) because the responses expressed as a percentage of potential are reasonably uniform across all sites.

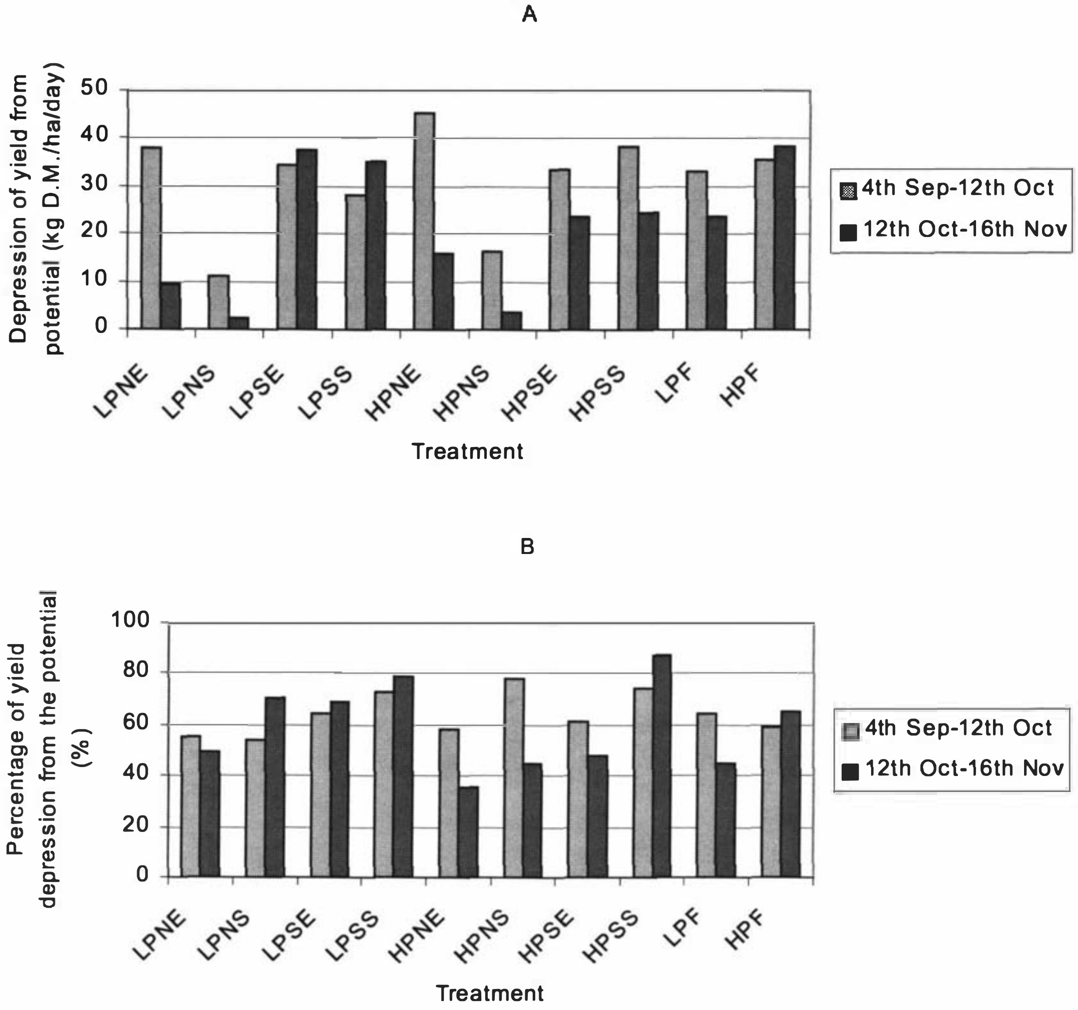


Figure 6.17 Pasture yield limitation for all sites displayed as a quantitative value (A) and a percentage (B) for the spring period.

During early summer (Figure 6.18A, growth period 7) the N restriction on pasture growth rate increased and there was a reasonably even pasture yield depression across all sites except for LPNS sites. The relatively even pasture yield depressions provided no statistically significant contrasts (Table 6.8).

In late summer (growth period 8) the restriction on pasture growth rate imposed by N availability was dramatically reduced with marginal pasture yield depressions recorded by all sites except for the HPNE, HPSS and HPF sites which had pasture yield depressions ranging from 15.1 - 18.5 kg D.M./ha/day. Statistical analysis showed that for the only time throughout the trial the HP treatment significantly increased pasture yield depression. Reasons for this will be investigated and discussed in section 6.4.

The relative non-responsiveness of the LPNS sites in early summer appears to be largely a result of climatic limitations as the yield depression was still high in relation to the potential yield (Figure 6.18B) indicating N limitations. The reduced pasture yield depression in late summer on all sites also appears to be due to climatic limitations (namely low soil moisture) except for the LPNE site and to a smaller extent the HPNE site where the yield depression relative to the potential yield was reduced. This indicates that those sites were able to supply enough N through mineralisation to almost meet potential growth rates.

In general, the northerly aspects had the highest pasture yield depressions throughout autumn and winter and the southerly and flat sites throughout the spring and summer. It should be noted that the yield depression expressed as a percentage of potential growth is high (30-90 %) on all sites throughout the year indicating that even on sites such as HPNE which grow adequate levels of clover (Gillingham *et al.,* 1998), there is a severe N deficiency.

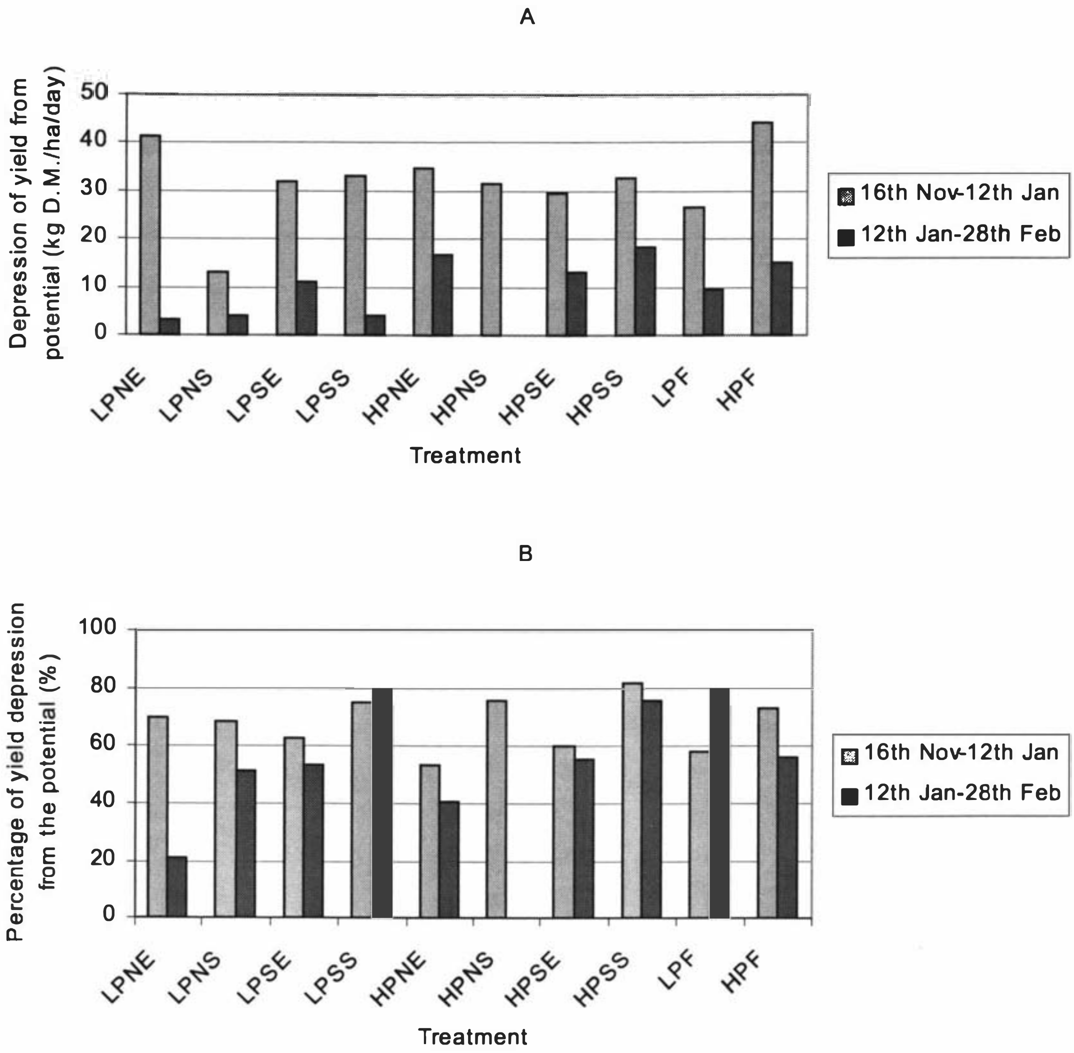


Figure 6.18 Pasture yield limitation for all sites displayed as a quantitative value (A) and a percentage (B) for the summer period.

Nitrogen responses (pasture yield limitations) in this study are well within the range of values found by other studies (Ball *et al.*, 1978; Field and Ball, 1978; Luscombe, 1979; Luscombe, 1980; Ledgard *et al.*, 1995) for similar sampling periods throughout the year. However, due to the varying N fertiliser rates, varying types of country, and varying sample periods it is hard to draw any conclusions about the relative responses of each treatment in relation to other trials. It is important to note though, that in terms of total N response over the period of a year, the N response is well above any values recorded by other authors even at high rates of N fertiliser. The maximum responses recorded by Ball *et al.* (1978), Luscombe (1980) and Ledgard *et al.* (1995) who used rates between 160 – 448 kg N/ha, was around 4000 kg D.M./ha/yr. That was recorded by Luscombe (1980) at a rate of 160 kg N/ha. Whilst an effective rate of 960 kg N/ha was applied in this study, well above any rate used in other studies, the large responses highlight the chronic N deficiency of these dry hill country pastures.

6.3.4 Estimated N fertiliser uptake

Figure 6.19 shows the apparent average total uptake of added fertiliser N by pasture at each site over the period of the trial. Values range between 290-436 kg N/ha. Therefore, as with the total pasture yield limitation, total N uptake between the sites did not vary much (except for the NS sites which were lower) when the total amount of N applied (960 kg N/ha) is considered.

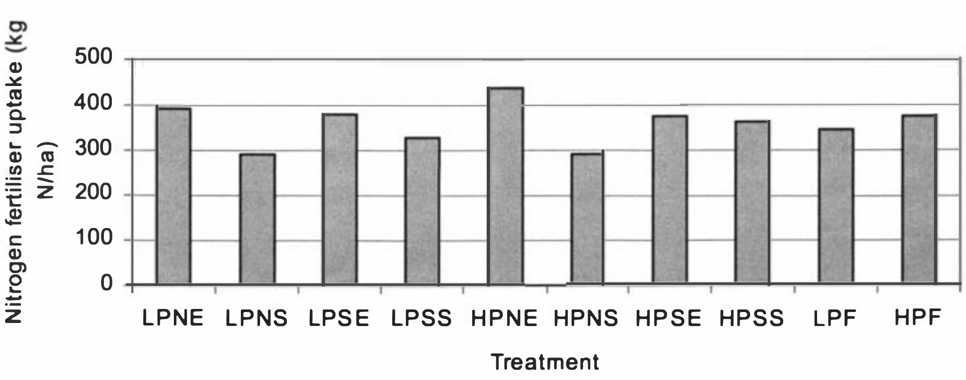


Figure 6.19 Apparent total uptake of added fertiliser nitrogen.

The results in Table 6.9A and Figure 6.20 show the apparent uptake of added fertiliser N at each site over the various growth periods throughout the trial. Uptake ranged from 4.6 kg N/ha on the LPNS site in growth period 8 to 91.6 kg N/ha on the HPNE site in growth period 5.

These estimates of N fertiliser uptake only reflect uptake during the assessment of pasture growth at each cage location (usually 4-6 weeks). No attempt was made to measure residual N fertiliser uptake after this time. In this experiment, N was applied at rates that were supposed to be unlimiting. Inspection of Table 6.9A suggests that in nearly all cases, more than sufficient fertiliser N (120 kg N/ha) had been applied to achieve this objective. The two exceptions in which growth may have been limited, were the HPNE sites in period 5 and the LPNS sites in period 3. Apparent uptake of added fertiliser N at these sites was 91.6 and 87.6 kg N/ha respectively. When losses and immobilisation of N are considered, growth may still have been slightly limited on these sites in those growth periods.

If it is assumed that sufficient fertiliser N had indeed been applied to make N non-limiting, then the data in Table 6.9B provide estimates of the magnitude of N deficiency at each site in each growth period expressed as kg N/ha/day.

The greatest N deficiency across all treatments appeared to have occurred in growth period 5 (start of spring) when the average uptake of N fertiliser reached 1.71 kg N/ha/day. The lowest average N uptake rate occurred in growth period 8 (the end of summer), when moisture stress limited the average uptake to 0.42 kg N/ha/day. The average N uptake by pasture on each site on a daily basis averaged for the entire trial period was reasonably even, except for the LPSS and NS sites, which had lower daily uptake rates. This was reflected in the apparent total annual N fertiliser uptake in Figure 6.19.

Table 6.9 Apparent uptake of added fertiliser N in each growth period expressed as A (kg N/ha) and B (kg N/ha/day).

A	1	2	3	4	5	6	7	8
LPNE	51.8	35.5	64.7	55.2	76.8	20.8	70.3	16.6
LPNS	44.3	30.9	87.6	68.7	21.7	7.0	28.0	4.6
LPSE	43.5	16.4	31.4	55.1	72.8	71.0	66.4	23.6
LPSS	47.7	25.1	19.6	26.6	65.5	69.3	66.4	8.4
HPNE	46.0	48.9	65.7	66.2	91.6	38.4	42.8	36.7
HPNS	38.0	30.0	77.8	70.0	24.4	8.7	40.9	#
HPSE	48.0	29.8	38.2	36.9	76.5	63.7	54.7	25.3
HPSS	51.7	22.4	24.2	37.6	82.3	48.8	65.5	31.7
LPF	46.7	16.6	37.9	48.6	72.3	52.2	51.9	19.2
HPF	60.0	22.6	35.0	48.8	66.2	58.8	51.8	30.5
Mean	**47.8**	**27.8**	**48.2**	**51.4**	**65.0**	**43.9**	**53.9**	**21.8**

B	1	2	3	4	5	6	7	8	*Mean
LPNE	1.40	1.11	1.10	0.99	2.02	0.59	1.23	0.35	**1.09**
LPNS	1.20	0.97	1.48	1.23	0.57	0.20	0.49	0.10	**0.81**
LPSE	1.18	0.51	0.53	0.98	1.92	2.03	1.16	0.50	**1.06**
LPSS	1.29	0.78	0.33	0.48	1.72	1.98	1.16	0.18	**0.91**
HPNE	1.24	1.53	1.11	1.18	2.41	1.10	0.75	0.78	**1.21**
HPNS	1.03	0.94	1.32	1.25	0.64	0.25	0.72	0.00	**0.81**
HPSE	1.30	0.93	0.65	0.66	2.01	1.82	0.96	0.54	**1.04**
HPSS	1.40	0.70	0.41	0.67	2.17	1.39	1.15	0.67	**1.01**
LPF	1.26	0.52	0.64	0.87	1.90	1.49	0.91	0.41	**0.96**
HPF	1.62	0.71	0.59	0.87	1.74	1.68	0.91	0.65	**1.04**
Mean	**1.29**	**0.87**	**0.82**	**0.92**	**1.71**	**1.25**	**0.95**	**0.42**	**0.99**

* = Mean calculated for entire length of trial, due to different lengths of growth periods.

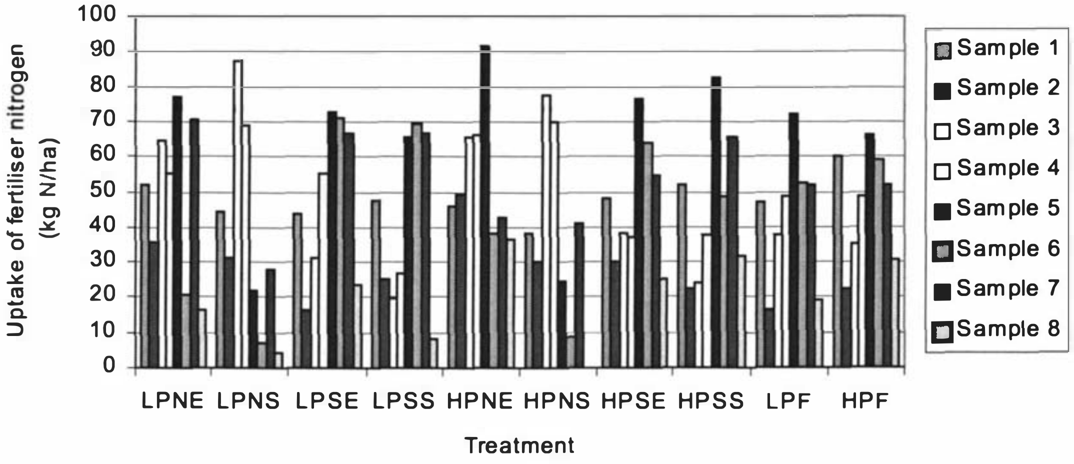


Figure 6.20 Apparent uptake of added fertiliser N on each site in each growth period

The total N uptake by pasture in the absence of added N and in the presence of unlimiting N (Figure 6.21), follows a similar pattern across sites as the total growth graph (Figure 6.1). However, it can be seen that the relative difference between the N limited sites and the unlimiting N sites in the N uptake graph (Figure 6.21) is much greater. This is due to the concentration of N in the pasture samples grown with non-limiting N being much greater compared with that in the N limited pasture - a similar finding to that of Ball *et al.* (1978) and Carran (1979).

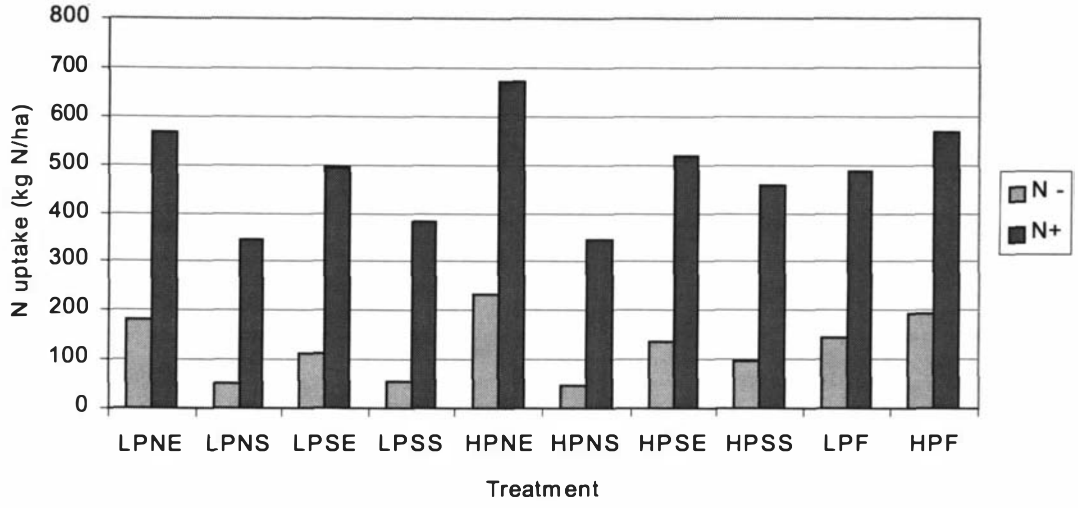


Figure 6.21 Total annual N uptake by pasture in the absence of added N and in the presence of non-limiting N at each site.

6.3.5 Clover Growth

Figure 6.22 shows the total annual growth of clover in the absence of added N and in the presence of non-limiting N for all sites. Values range from 0 kg D.M./ha for the LPNS site in the absence of added N to 1497 kg D.M./ha for the HPNE site in the presence of non-limiting N. The main points to note are that HP plots produced significantly more clover than the LP plots (Table 6.2). This was true for every site except the flat sites. The NE sites also produce significantly more clover than any other site. Other points of interest are that there was little to no growth on the NS sites and that N fertiliser did not have an effect on clover growth. Further discussion of the effect of N fertiliser on clover growth is presented later in this section.

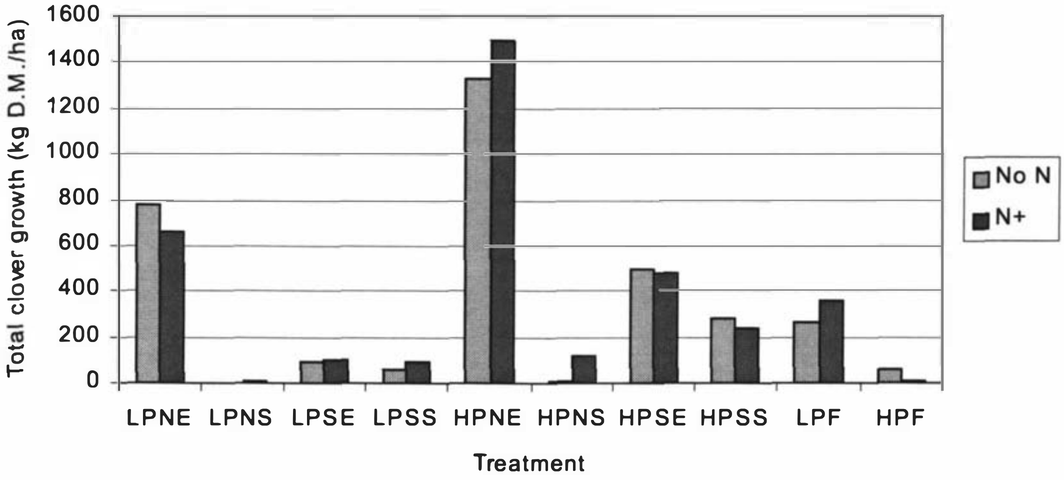


Figure 6.22 Total growth of clover (kg D.M./ha) for each site for the trial period.

The results in Tables 6.10 and 6.11 and Figures 6.23 and 6.24 show the clover growth rates in the absence of added N, and in the presence of non-limiting N respectively, for all sites over the 8 growth periods. Clover growth rates in the absence of added N, ranged from 0 kg D.M./ha/day for many of the sites throughout the trial period to 13.0 kg D.M./ha/day for the LPNE sites in growth period 5. The clover growth rates in the presence of non-limiting N range from 0 to 16.1 kg D.M./ha/day for the LPNE sites in growth period 5. The major observation however, was the low amounts of clover growth throughout the trial period. This is a factor commonly associated with dry hill country pastures (Suckling, 1975; Ball *et al.,* 1982; Chapman and MacFarlane, 1985).

Table 6.10 Clover growth rates for sites in the absence of added N (kg D.M./ha/day) for the 8 growth periods.

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LPNE	1.03	0.69	3.00	0.51	12.96	0.24	0.02	0.25
LPNS	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00
LPSE	0.04	0.05	0.00	0.00	0.93	0.81	0.53	0.01
LPSS	0.38	0.08	0.00	0.00	0.67	0.56	0.00	0.00
HPNE	1.36	0.70	5.66	10.61	5.67	0.88	0.46	1.04
HPNS	0.00	0.00	0.00	0.01	0.13	0.00	0.00	0.00
HPSE	0.30	1.53	0.30	0.55	3.64	1.53	2.59	1.04
HPSS	0.39	0.06	0.01	3.49	1.76	0.00	0.00	0.04
LPF	0.28	1.12	0.67	0.58	0.28	3.76	0.01	0.00
HPF	0.42	0.14	0.21	0.01	0.10	0.70	0.02	0.00

Table 6.11 Clover growth rates for sites in the presence of non-limiting N (kg D.M./ha/day) for the 8 growth periods.

Period	1	2	3	4	5	6	7	8
LPNE	0.00	0.14	0.62	0.18	16.06	0.00	0.00	0.00
LPNS	0.00	0.00	0.00	0.01	0.18	0.00	0.00	0.00
LPSE	0.00	0.05	0.00	0.36	1.44	0.48	0.11	0.00
LPSS	0.00	0.04	0.00	0.21	1.35	0.56	0.19	0.00
HPNE	0.72	1.94	7.71	11.36	7.47	0.66	0.02	0.19
HPNS	0.00	0.00	0.00	0.73	2.09	0.00	0.00	0.00
HPSE	0.00	1.03	0.35	1.74	5.10	2.53	0.00	0.94
HPSS	0.00	0.04	0.03	0.92	3.73	1.20	0.02	0.01
LPF	0.02	0.48	0.17	1.69	1.77	4.79	0.00	0.00
HPF	0.00	0.02	0.11	0.01	0.05	0.00	0.00	0.00

Table 6.12 Statistical analysis of clover growth rates of all sites (N limiting and N non-limiting) combined for the 8 growth periods.

Contrast	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Phosphate	-	-	**	**	-	-	-	**
Nitrogen	*	-	-	-	*	-	-	-
N*P	-	-	*	-	-	-	-	-
NE vs. NS	*	*	**	*	**	-	-	-
NE vs. SE	*	-	**	-	**	-	-	-
NE vs. SS	-	*	**	-	**	-	-	-
NE vs. F	-	-	**	-	**	-	-	-
NS vs. SE	-	-	-	-	-	-	*	-
NS vs. SS	-	-	-	-	-	-	-	-
NS vs. F	-	-	-	-	-	-	-	-
SE vs. SS	-	-	-	-	-	-	-	-
SE vs. F	-	-	-	-	-	-	*	-
SS vs. F	-	-	-	-	-	-	-	-
North vs. South	-	-	*	-	*	-	-	-
Easy vs. Steep	-	*	*	-	**	-	-	-
North vs. Flat	-	-	-	-	**	-	-	-
South vs. Flat	-	-	-	-	-	-	-	-
Easy vs. Flat	-	-	-	-	**	-	-	-
Steep vs. Flat	-	-	-	-	-	-	-	-

* = $P < 0.05$; ** = $P < 0.01$.

As a result of the scattered nature of clover growth on the trial site, statistical analysis (Table 6.12) shows that the positive effect of P on clover growth was only statistically significant in growth periods 3, 4 and 8. The increased P fertility would generally be expected to increase the clover content and productivity (Dodd and Ledgard, 1999).

The N fertiliser had a significant effect on clover growth in growth periods 1 and 5. In growth period 1 sites in the absence of added N produced significantly higher amounts of clover than did non-limiting N sites, however the pattern was reversed in growth period 5. It is a well reported phenomenon that N fertiliser application decreases clover content in pasture due to other grasses out-competing clover and starving clover of sunlight (Crush *et al.,* 1982; Ledgard *et al.,* 1995). Therefore, it may have been expected that the negative effect of N fertiliser on the clover content of the trial pastures may have been greater and more consistent than occurred here. However, the effect of N fertiliser on clover growth is usually a longer term phenomenon and is closely related to management policies which allow the pasture to become rank, thus depriving the clover plants of light. In this study the growth periods were relatively short, and the initial clover content in the pasture was often low. This may explain why the N fertiliser effect was reasonably small and non-existent in some growth periods. Other studies have also found that N fertiliser sometimes had little to no effect on clover content for similar reasons (Scott, 1972; Ball *et al.,* 1978; Luscombe, 1979).

The statistical analysis of the seasonal data reinforced the conclusions made earlier concerning total annual clover production – namely the positive effect of high P status on clover growth, and the greater clover growth on the NE sites compared to many others. These contrasts do not occur uniformly throughout the year- being mainly apparent in early winter (growth period 3) and early spring (growth period 5) (Table 6.12).

It is interesting to note that although overall annual clover growth rates were highest on the HPNE sites, the LPNE sites produced the highest individual clover growth rates for a single growth period, in both the absence of added N and also in the presence of non-limiting N. In both cases, the high value recorded on the LPNE sites was an outlier and well above other values recorded on the sites throughout the trial period.

This perhaps highlights an important consideration with respect to analysis of pasture composition in a trial such as this. Due to the very low content and sparse scattering of clover in the pastures, and the relatively small size of the pasture growth cage in relation to overall paddock size, the placement of the cage can be crucial. For instance, if the cage was placed on two vigorous clover plants the measured clover content may be high, however the cage could also be placed just to the side of the two plants and register no clover growth at all. Therefore, any conclusions as to clover content in this trial must be treated carefully, except for the fact that the clover content of the pasture was low and in the case of the NS sites non-existent.

The lack of clover highlights the points raised in section 6.3.3 on the limitations that N availability place on pasture growth. Dry hill country is seriously deficient in N for pasture growth, largely as a result of the lack of clover growth and subsequent lack of N fixation, resulting in large responses to N fertiliser. Estimates of N fixation of 13 kg N/ha/yr (Grant and Lambert 1979) are probably average for this type of country. Obviously sites with higher clover contents such as HPNE and HPSE sites will provide higher rates of N fixation, but generally the remainder of the hill pasture will be starved of adequate N inputs.

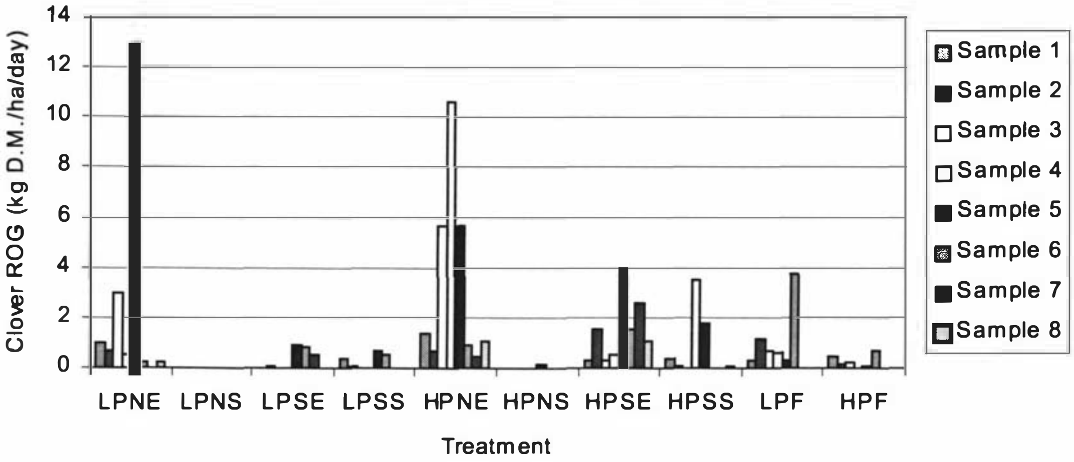


Figure 6.23 Clover growth for sites in the absence of added N for the 8 sample periods.

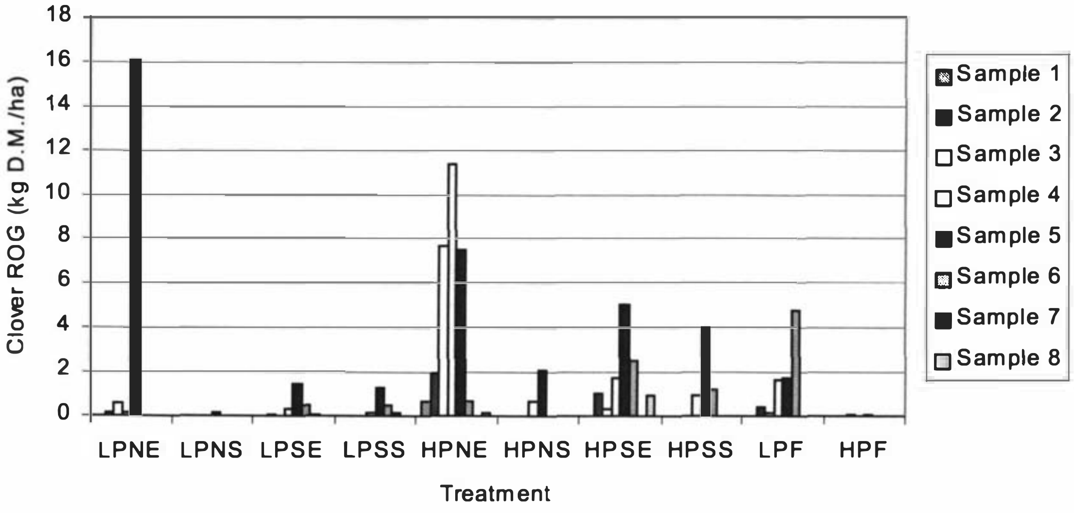


Figure 6.24 Clover growth for sites in the presence of non-limiting N for the 8 sample periods.

6.4 DISCUSSION

The results in Section 6.3 highlight some interesting factors influencing pasture production, N response and pasture composition between varying aspects, slopes, and fertility treatments throughout the year. This section will discuss the reasons for the variations and the major factors causing them.

6.4.1 Nutrients

There are many nutrients which influence pasture growth, however, this study only examined the effects of N and P.

6.4.1.1 Nitrogen

As has been mentioned, N is viewed as the key nutrient driving pasture production. The pasture growth results displayed in this chapter totally support this theory. The application of N fertiliser caused a significant increase in total annual pasture production and seasonal pasture growth rates at each site in every growth period throughout the year (Figure 6.1 and Table 6.13). This indicates that in the absence of N fertiliser the availability of soil N is placing major restrictions on pasture growth throughout the year. The extent of this restriction varied within sites throughout the year as well as between sites. Generally speaking however, the difference between potential and actual annual pasture production was proportional to the total annual growth of the plots in the absence of added N (see Figure 6.25). However, when individual plots in individual growth periods are compared, the relationship becomes very scattered (Figure 6.26). The good relationship between pasture yield depression and pasture yield in the absence of added N that was found when total growth data were compared, may have been expected if it was assumed that nutrient restrictions are equal for every site. However, Figure 6.26 shows that this was not the case and there is a confounding effect between climatic conditions and N deficiency – on the limitation on pasture growth.

The relationships discussed above highlight two key issues with respect to dry hill country. The first is that the biggest annual depression in pasture yield (relative to potential) occurs on sites with the biggest annual total growth in the absence of added N (Figure 6.25). It may have been thought that if growth conditions were good enough to provide good growth for pasture, clover growth would be increased, and subsequently the supply of N, which would reduce the extent of N deficiency. However, this was not observed, and it can therefore, be assumed that on this type of country N is deficient to such an extent that even sites which have the best conditions for clover growth are still severely restricted by N supply. This is supported by the clover growth data (Figure 6.22), which shows that the highest annual total clover growth was recorded on the HPNE site which also appeared to have the greatest restriction on potential pasture growth due to N deficiency (Figure 6.14).

The second issue is that the major pasture growth limitations alternate between being predominantly climatic and predominantly N supply throughout the year. For instance, NS sites in winter have adequate moisture and sunlight to sustain high growth rates, however in the absence of added N, pasture growth was low with soil N availability being the major restriction on growth. In contrast, SS sites in winter are likely to be more restricted by temperature than N supply.

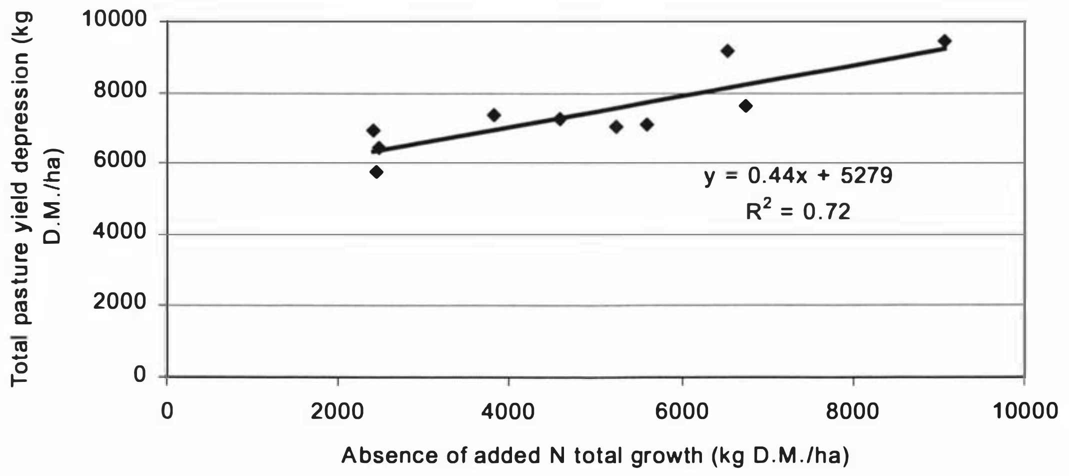


Figure 6.25 Relationship between total growth in the absence of added N and total pasture yield depression.

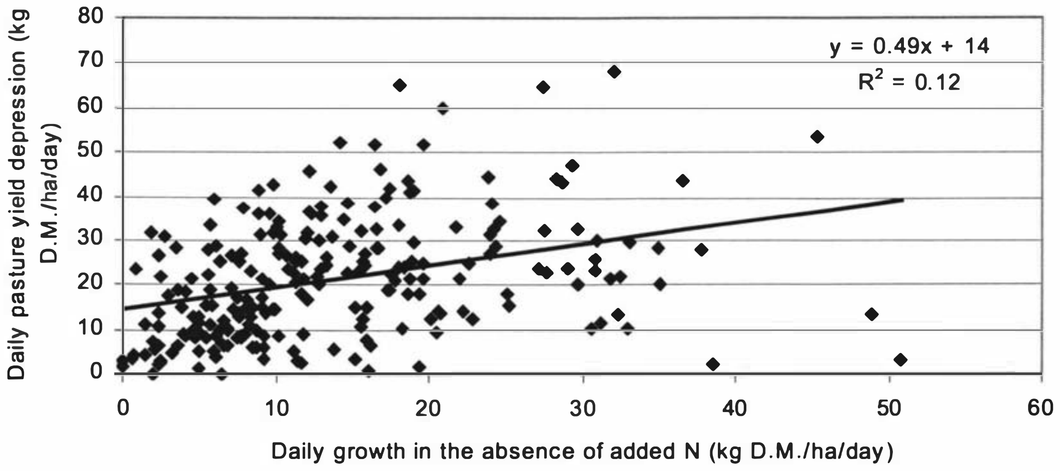


Figure 6.26 Relationship between individual pasture growth rates at each site in the absence of added N and the pasture yield depression at each site for each growth period.

Table 6.13 Pasture growth statistics (when N limited and N non-limiting sites are considered together) for the 8 growth periods.

Contrast	1	2	3	4	5	6	7	8
Phosphate	-	*	*	-	-	*	-	*
Nitrogen	**	**	**	**	**	**	**	**
N*P	-	-	-	-	*	-	-	*
NE vs. NS	*	*	**	*	**	**	**	**
NE vs. SE	*	**	**	**	**	*	-	-
NE vs. SS	*	**	**	**	**	-	*	**
NE vs. F	-	-	**	-	*	*	-	-
NS vs. SE	-	-	*	-	**	**	**	*
NS vs. SS	-	-	**	*	**	**	-	-
NS vs. F	**	-	-	-	**	**	**	-
SE vs. SS	-	-	-	-	-	*	-	-
SE vs. F	*	-	**	*	-	-	-	-
SS vs. F	**	-	**	**	*	*	-	-
North vs. South	-	**	**	**	-	**	-	-
Easy vs. Steep	-	**	**	*	**	**	**	**
North vs. Flat	*	-	-	-	-	**	-	-
South vs. Flat	**	**	**	**	-	-	-	-
Easy vs. Flat	*	-	-	-	-	-	-	-
Steep vs. Flat	**	**	**	*	**	**	*	-

* = $P < 0.05$; ** = $P < 0.01$.

If attempts are made to relate pasture growth to soil nutrient levels it is found that there is no relationship between soil ammonium and nitrate levels and pasture growth in the absence of added N (data not shown). As was discussed in Chapter 5, the transient nature of ammonium and nitrate in soil (due to large and variable inputs and losses from the mineral pool) means that pasture growth is unlikely to relate well to either test. For instance the highest growth rates on the southerly and flat sites were found in the sixth growth period in mid spring (Table 6.3). However, there was little or no nitrate measured on any of these sites at the start of the growth period (Table 5.7). Obviously pasture uptake of nitrate matched inputs via mineralisation and nitrification and thus little or no nitrate was found in the soil samples. Further discussion on this point can be found in Chapter 5.

The pasture growth rates on the plots in the absence of added N however, related somewhat better with the mineralisable N soil tests (Figure 6.27). Whilst there was not a strong relationship, if the NE sites are removed from the correlation, an R^2 value of 0.58

(Figure not shown) was obtained. The NE sites have anomalously high pasture growth rates in relation to the measured mineralisable N values.

This raises a key point in relation to the mineralisable N test. The mineralisable N test is measured under "standard environmental" conditions – but in the field the conditions will be more conducive to mineralisation on some sites than others, due to more favourable temperature and moisture conditions. This is demonstrated by the anomalous behaviour of the NE sites, which have increased N mineralisation rates due to higher soil temperatures.

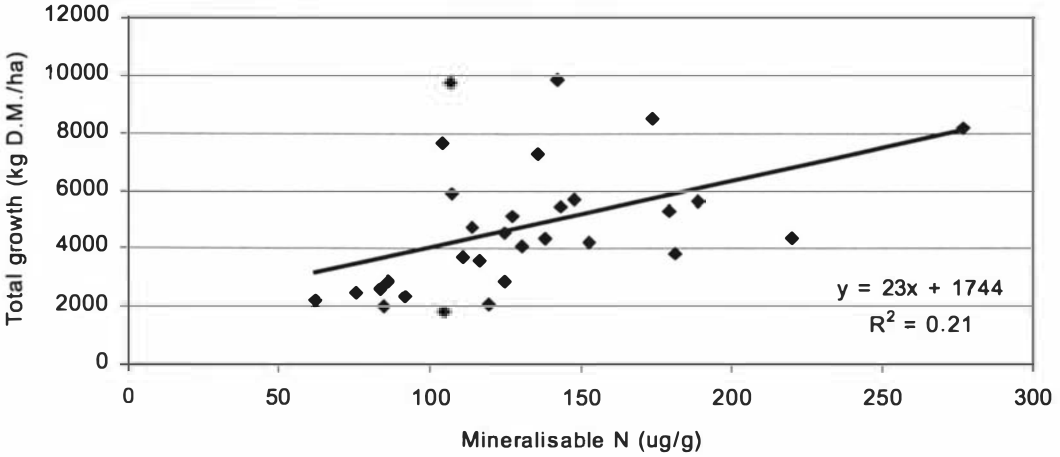


Figure 6.27 Relationship between average soil mineralisable N throughout the year at each replicate and total annual growth of pasture in the absence of added N.

Mineralisable N was also linearly related to the "responsiveness" of the pasture to N fertiliser. This "responsiveness" was calculated as the difference in annual pasture production between +N and –N treatments expressed as a percentage of the +N (potential) production (Figure 6.28). The linear relationship had an R^2 value of 0.34, and shows that as the average mineralisable N value increased, the percentage depression from potential growth decreased – i.e. the N limitation decreased as mineralisable N increased.

It therefore appears that the mineralisable N test has some value in providing an indication of the N supplying potential of the soil. Keeney and Bremner (1966) found that the mineralisable N test related well to N uptake. However there may be room for improving the mineralisable N test for hill soils by incorporating a temperature correction function, which will account for some of the temperature differences between aspects and slopes in hill country.

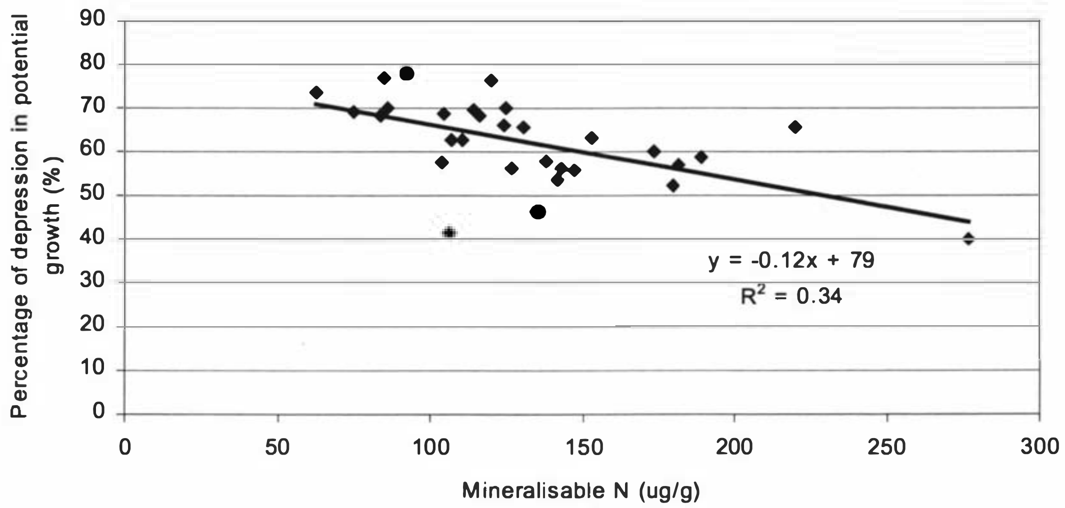


Figure 6.28 Relationship between the percentage of depression in potential growth and average mineralisable N throughout the year at each replicate.

6.4.1.2 Phosphorus

There was a P response from both grass and clover in both the absence of added N and in the presence of non-limiting N in terms of total annual production and production in some individual growth periods. The effect is clearly apparent in Figure 6.29 when total annual pasture production was averaged across all sites. The continued existence of a P response in the presence of non-limiting N suggests that addition of P fertiliser was overcoming an actual P deficiency in grasses – rather than reducing N deficiency by stimulating clover growth. This is supported by Figure 6.30 which shows the total annual P response of grass (clover not included). It would therefore appear that P was sufficiently deficient to create a positive P response in pasture production on all sites (independent of a surrogate action through N), with the exception of SE sites.

Of particular note however, is that the N response was far greater than the P response, indicating that N was the key nutrient in promoting pasture growth (Figure 6.29).

The P response was not uniform across sites or with seasons, and tended to be greatest in the presence of non-limiting N when soil moisture was limiting (but before full drought) (Table 6.5). This is also highlighted through P only having a significant effect on N responsiveness in growth period 8 (end of summer), when HP sites appeared to be more severely restricted by N availability than LP sites.

A possible explanation for the increased P response during dry periods is that the increased P fertility increased pasture rooting depth (Matthew *et al.,* 1991), which subsequently increases the plants ability to source water, as soil moisture levels declined. Therefore, it may be the case that much of the observed P response was due to "extra growth days" during dry periods, rather than a direct pasture growth rate response due to a P deficiency being overcome.

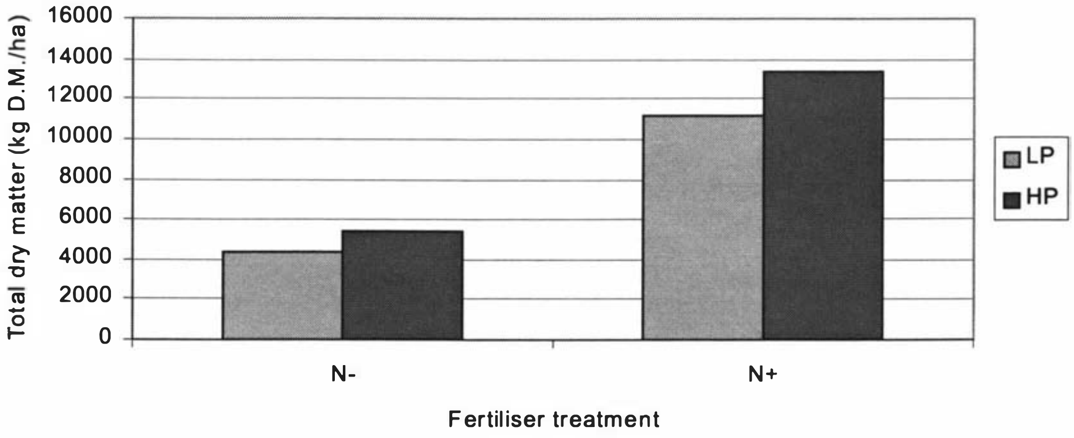


Figure 6.29 Total pasture growth averaged across all sites showing the effect of phosphate fertility.

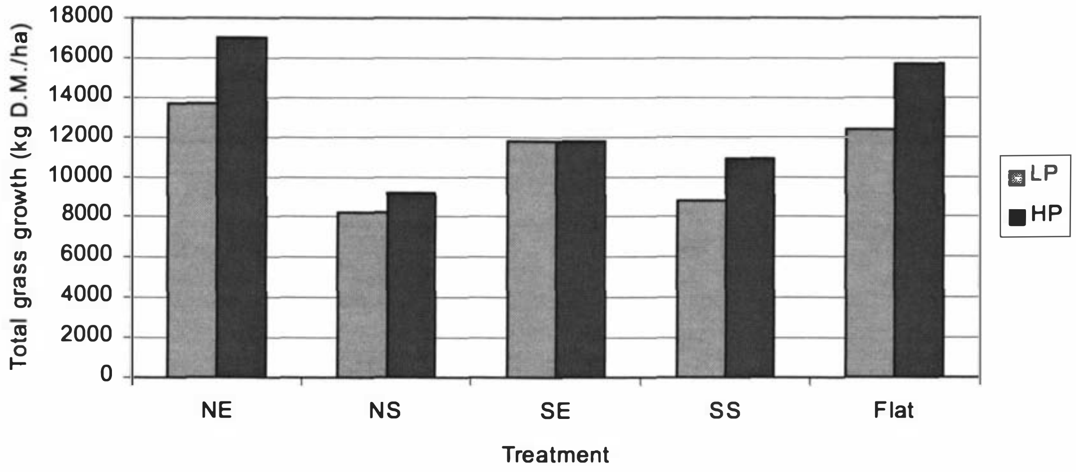


Figure 6.30 Total grass growth on sites in the presence of non-limiting N.

Moir (2000) found that pasture growth related well to Olsen P up to a value of around 30 µg P/g. There was however, no relationship between pasture growth and Olsen P in this study.

There are two main reasons why this study might have varied from the findings by Moir (2000). Firstly the Olsen P values reported in this study (Chapter 5) are perhaps not accurate measures of the amount of P that was available for pasture growth at the sites from which they were measured due to factors such as stoniness (see Chapter 5 for further details). This was compounded by the fact that on those stony NS sites, pasture growth is limited by other factors such as low pasture density and low soil moisture levels. Therefore, the pasture growth is not likely to relate well to the Olsen P values on those sites.

Secondly, the high P sites used in Moir (2000) study had received high rates of P fertiliser for up to 25 years. This may have allowed sufficient clover growth over this time to build up the N pool, and thus provide higher amounts of N on the HP sites. In this study the HP sites have only had raised P fertilities for five years, which combined with the dry nature of the site (which limits clover production), will have reduced possible extra N inputs from clover N fixation.

Whilst Moir (2000) found a good relationship between Olsen P and pasture growth, that study found no relationship between mineralisable N and pasture growth as was measured in this study.

Therefore in hill country, the usefulness of the Olsen P test as an indicator of potential pasture yield can be questioned. The Olsen P test may be useful for assessing the availability of P in the soil, but where soil moisture and clover levels are seasonally low, the expected link between HP status and N fixation will not exist.

6.4.2 Micro-climatic effects

As has been discussed above, pasture growth varied dramatically between aspects and slopes throughout the year and, with it the extent to which pasture growth was limited by N availability. A large part of this variation resulted from the interaction between climate and topography. In this context "climate" refers to all environmental parameters, including temperature, rainfall, sunlight and wind.

6.4.2.1 Temperature and Radiation

Temperature and sunlight will be discussed together as they are closely related. They have a major effect on pasture growth by providing the energy for photosynthesis and many of the soil processes determining nutrient availability. Soil moisture is also affected by energy inputs, but it will be discussed separately in the next section.

Removing major nutrient constraints on pasture growth in the HP plus N sites allowed the major climatic effects which include energy inputs to be examined. In the HP plus N sites (Table 6.5) pasture growth generally decreased through autumn and winter and then peaked in spring and early summer, before decreasing at the end of summer. When the drop off in pasture growth rate through autumn and winter is examined in more detail it is apparent that this occurred most obviously on the southerly aspects. Growth rates on the NE slopes decrease only slightly during winter and the NS slopes maintained a virtually constant growth rate over winter. Pasture production on the flat sites was between that on southerly and northerly sites through this period.

The drop off in production through winter on the southerly and flat sites is easily explained by energy inputs. Through autumn and winter the sun becomes lower in the sky, and overall temperatures drop. In the southern hemisphere, this means that the southerly and flat aspects receive less sunshine while the northerly aspects, particularly steep slopes, receive relatively more (this will be discussed in more detail in Chapter 7 in relation to evapotranspiration). The difference in energy inputs on north and south aspects throughout autumn and winter is highlighted in the soil temperature data in Chapter 5 (Figure 5.2). Therefore, the continuation of higher pasture growth levels on the northerly aspects is due to higher energy inputs on these sites than on southerly aspects. The effect is highlighted in the statistical analysis of the pasture growth data (Table 6.6) which shows that the northerly sites produce significantly more pasture than the southerly sites in growth periods, 2, 3 and 4.

Energy inputs are high on all aspects and slopes throughout spring and summer, and any decline in pasture growth rates observed on the northerly sites in particular, and on all sites in growth period 8, are due to moisture limitations. Further discussion of this will be given in the next section.

While the above-ground energy inputs affect pasture growth primarily by limiting the rate of photosynthesis, the soil temperature also affects pasture growth (see section 2.5.1.1). Ryegrass growth ceases at 6°C, whilst clover ceases at 9°C (Chapman and MacFarlane, 1985; Whitehead, 1995). The soil temperature data (Section 5.3.2) shows that in winter the soil temperature on southerly aspects fell well below 10°C and even dropped below 5°C. Soil temperature on the NS sites never fell below 10°C, while soil temperatures on the NE sites declined to around 9°C. Figure 6.31 shows the relationship between the average soil temperature at 10 cm depth for the NE, NS, SE and SS sites over the first four growth periods (when there were no moisture restrictions) and the average daily pasture growth rates on the corresponding HP+N sites.

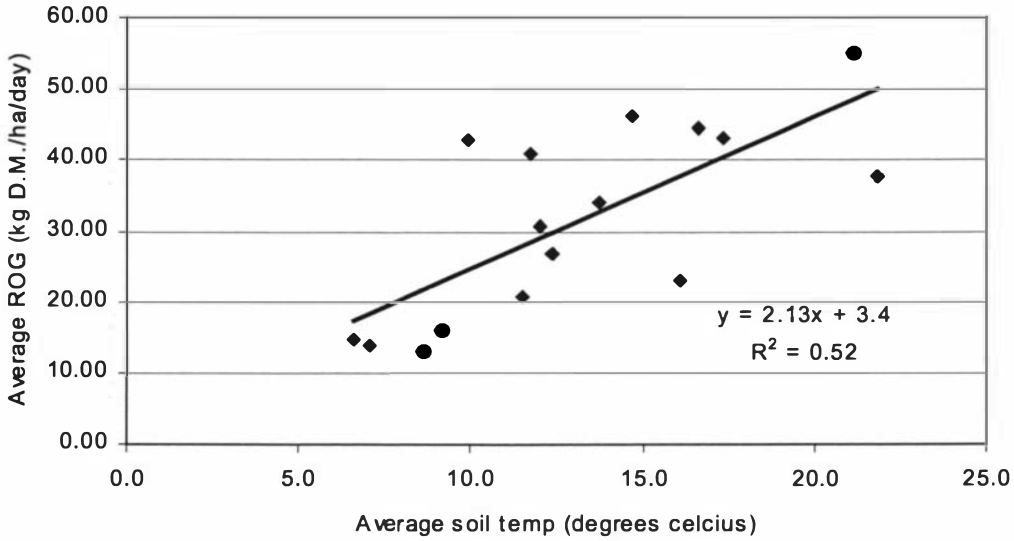


Figure 6.31 Average soil temp on NE, NS, SE and SS sites for the first four growth periods vs. the average growth on the corresponding HP + N sites.

6.4.2.2 Soil moisture

Moisture is a very important factor for pasture growth for three reasons. Firstly, all cellular processes require water to function. Secondly, water is required for the uptake of nutrients into the plant, and thirdly water is required for evaporative cooling. Pasture growth can be limited when the topsoil is dry, as it restricts the movement of valuable nutrient ions, even though adequate water is available from lower depths (Garwood and Williams, 1967; Lemaire and Denoix, 1987).

The variations in gravimetric soil moistures between the sites and throughout the year, were discussed in detail in Chapter 5. The low soil moisture contents on the NS, and at times the NE sites, in spring and summer can explain the decreased pasture growth rates throughout this time. In the final growth period at the end of summer, the pasture growth of all sites was severely limited due to moisture restrictions.

No overall relationship was found between pasture growth and measured soil moisture. There are likely to be a number of reasons for this. Firstly the soil moisture measurements were taken at the start of each growth period and are therefore not necessarily representative of the soil moisture over the duration of each growth period. Secondly, pasture growth is only affected by soil moisture when soil moisture becomes limiting. At most times of the year on the southerly and flat sites the soil moisture was well above levels which would limit pasture growth, and there would be no expected increases in growth with increased moisture levels. Thirdly, due to the differing moisture holding capacities and rooting depths of the pasture on the different aspects and slopes, the level at which moisture became limited varied. Fourthly, and probably most importantly, the time of the year when moisture levels are at their highest is in the winter when growth rates are at their lowest – for most sites. Therefore, the relationship is generally inverse through this time and positive through the spring and summer.

The combined effect of energy inputs and soil moisture levels will be discussed in terms of one factor (evapotranspiration) in the next chapter. The discussion above has served to differentiate the two factors and show individually how they affect pasture growth throughout the year. Figures 6.32 and 6.33 give a good indication of the combined effects of all of the factors mentioned in this Chapter on slope and aspect. Figure 6.32 shows that the easy slopes produce far more pasture on average than the steep slopes both in the absence and in the presence of non-limiting N. This is likely to be due to the combined effect of a lack of energy inputs on the SS slopes in winter restricting pasture growth and the moisture restrictions on the NS slopes in the spring and summer. Figure 6.33 shows that on average, the flat sites produced more pasture than the northerly sites which in turn produce more than the southerly sites. This is despite the fact that the NE sites produced the highest individual pasture growth rates and highest total growth. The soil moisture restrictions in the spring and summer on mainly the NS sites however, drags the average for northerly aspects down (as mentioned in sections 6.3.1 & 6.3.2). The low growth on the southerly sites is due again to the low energy inputs over autumn and winter. The flat sites lie somewhere in between in terms of both energy inputs and soil moisture and are therefore, not affected to the same degree, and on average, produce the most pasture. It is interesting to note that the averaged effects of slope and aspect on pasture production are not nearly as large as the effect of nitrogen fertiliser.

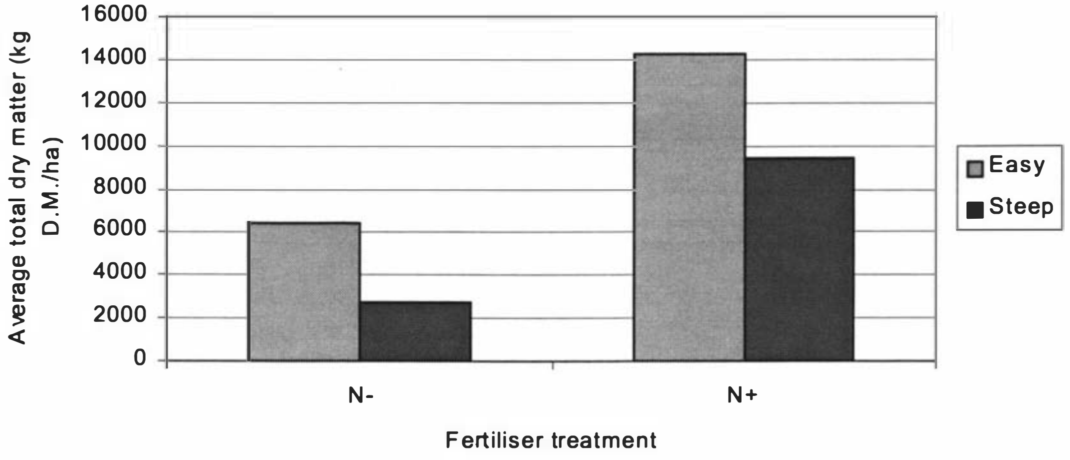


Figure 6.32 Average total pasture growth with or without N fertiliser showing the effect of slope.

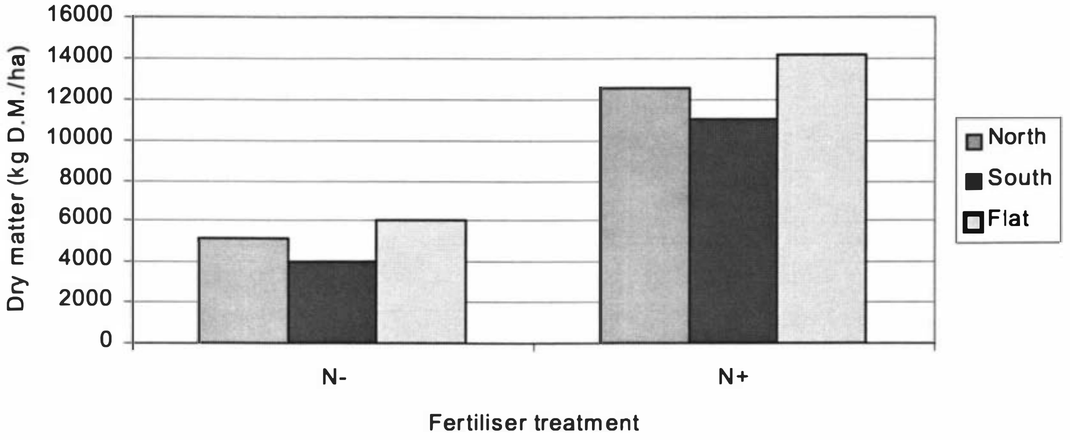


Figure 6.33 Average total pasture growth with or without N fertiliser showing the effect of aspect.

6.4.3 Summary of pasture growth constraints

A summary of the major constraints on pasture growth throughout the four seasons of the year can be found in Tables 6.14, 6.15, 6.16 and 6.17. The Tables highlight the points raised in the discussion on factors affecting pasture growth. The constraints listed are likely to be the main factors which limit pasture growth at certain periods throughout the year. It may be noted that while factors such as temperature and sunlight might control growth on northerly sites during the winter, these factors have not been listed as constraints on northerly sites in this period as adequate levels of pasture production continue on those sites relative to other parts of the landscape.

Table 6.14 Summary of possible pasture growth constraints in autumn.

Constraint	**NE sites**	**NS sites**	**SE sites**	**SS sites**	**Flat sites**
N supply	✓	✓	✓	✓	✓
P fertility					✓
Soil moisture	*	*	*	*	*
Soil temperature					
Sunlight			✓	✓	✓

✓ = the constraints found in this study
* = the constraints also found in "normal" years

Table 6.15 Summary of possible pasture growth constraints in winter.

Constraint	**NE sites**	**NS sites**	**SE sites**	**SS sites**	**Flat sites**
N supply	✓	✓	✓	✓	✓
P fertility					
Soil moisture	*	*			
Soil temperature			✓	✓	
Sunlight			✓	✓	✓

✓ = the constraints found in this study
* = the constraints also found in "normal" years

Table 6.16 Summary of possible pasture growth constraints in spring.

Constraint	**NE sites**	**NS sites**	**SE sites**	**SS sites**	**Flat sites**
N supply	✓	✓	✓	✓	✓
P fertility	✓				
Soil moisture	✓	✓			
Soil temperature					
Sunlight					

✓ = the constraints found in this study
* = the constraints also found in "normal" years

Table 6.17 Summary of possible pasture growth constraints in summer.

Constraint	**NE sites**	**NS sites**	**SE sites**	**SS sites**	**Flat sites**
N supply	✓	✓	✓	✓	✓
P fertility	✓	✓	✓	✓	✓
Soil moisture	✓	✓	✓	✓	✓
Soil temperature					
Sunlight					

✓ = the constraints found in this study
* = the constraints also found in "normal" years

6.4.4 Potential for N fertiliser use

This study has made clear, the enormous constraint that N non-availability places on potential pasture production in summer-dry hill country. Results from this trial indicate that on an annual basis, pasture growth was restricted to approximately 38 % (on average) of its potential production levels, yielding 7417 kg D.M./ha/yr (on average) less than could potentially be grown by the existing sward.

Fertiliser use on the country in the past has been primarily limited to using superphosphate, and within the current AgResearch study large applications of P fertiliser have been made to raise the P fertility of some sites. The pasture yield results in this study raise some serious questions about the efficiency and relative productivity of using P fertiliser to stimulate clover growth and subsequent N inputs into the soil/pasture system, when soil moisture and associated legume persistence and production is low.

Clover growth on the trial was minimal on most sites throughout the year and this is reflected in the severe limitation to pasture growth imposed by N deficiency. Therefore, there may be room for moving away from the conventional approach of using P fertiliser to boost pasture production (through a surrogate action of N), to selectively using N fertiliser.

To achieve optimum use of N fertiliser it is necessary to understand at what times of the year, and on what landscape units it is most required. The uptake data are useful in this regard.

As an example, growth period 5 (start of spring) will be considered when pasture yield depressions due to N deficiency are greatest. The maximum potential N uptake occurred on the HPNE sites, where potential uptake levels of 3.33 N/ha/day were recorded. Measured available soil N at the start of the growth period showed that there was 9.00 kg N/ha available down to a depth of 75 mm. Therefore, assuming that most of the available mineral N occurred in the top 75 mm (and that it is all available for uptake), the results would indicate that there was approximately only 3 days worth of potential growth stored in the soil (in reality, not all of that N will be available for uptake). This highlights two key points in relation to the availability of N in hill country.

Firstly, it highlights the absolute deficiency of N in dry hill country, where available soil N storage pools store relatively little N in relation to the potential uptake rates. This leads to the second important issue - the importance of the mineralisation process to pasture growth. In periods of high potential growth the pasture is likely to be utilising soil N as soon as it is becoming available (essentially a hand to mouth scenario), thus it becomes the rate limiting step determining the pasture growth rate.

In contrast on LPNE sites in growth period 4 (end of winter), there was sufficient mineral N in the soil (50.0 kg N/ha), to last for 50 days at the maximum N uptake rate of 0.99 kg N/ha/day. Clearly the need for N fertiliser is less in this situation.

At present, the general approach to N fertiliser application on hill country is to apply one rate, once a year, to all slopes and aspects. This is due to a number of reasons including limitations in topdressing technology, cost restrictions and lack of knowledge of potential N responses. At present however, work is being carried out to investigate the potential for varying aerial application rates according to slope and aspect, and meat and wool prices are increasing, making N fertiliser application a more viable economic option. Therefore, if it was possible to apply N fertiliser at differing rates, the results in this study provide information on where and when such amounts should be applied.

If fertiliser is to be applied to all slopes and aspects, a typical application rate of N fertiliser on dry hill country would be approximately 25 kg N/ha (O'Connor and Gregg, 1971). Table 6.9A shows the average uptake of fertiliser N in each growth period. This information therefore, provides a useful indication of whether an application of 25 kg N/ha would be fully utilized if it was applied across all slopes and aspects.

The average uptake of fertiliser N was above 40 kg N/ha for every growth period except periods 2 and 8 when uptakes of 27.8 and 21.8 kg N/ha occurred respectively. Without considering residual responses, fertiliser application in these periods (late autumn and late summer) would therefore not be fully utilized within 4-6 weeks at these times of the year.

However, in general, rates of N fertiliser uptake exceeded 40 kg N/ha for most sites throughout the year (Table 6.9), indicating that there is potential to increase fertiliser application rates to above current levels, and for many applications to provide a response as opposed to one application at a low rate.

If it is possible to apply differing rates of fertiliser to different aspects, a breakdown of the potential could be as follows. In early autumn good responses are found on all sites, however in late autumn the response on the southerly and flat sites decreases while the northerly sites keep producing good responses. This pattern follows throughout winter. From the start of autumn to the end of winter the average uptake of added N on the northerly sites is 220 kg N/ha, as opposed to 145 kg N/ha on the southerly and flat sites.

With the onset of spring all sites receive adequate energy to support good N responses however, moisture becomes a limiting factor. This dramatically reduces N responses on the NS sites, and the NE sites are limited later in spring. The potential for N response continues to be high on the southerly and flat sites until mid summer when it decreases due to moisture restrictions. If rainfall is adequate the NE sites are likely to respond the same as the southerly and flat sites but the NS sites will still have limited responses. The average uptake of added fertiliser N on the southerly and flat sites from spring through to the end of summer was 206 kg N/ha whilst for instance the average uptake on the LPNS site was 61 kg N/ha.

The discussion above outlines the areas and times where the potential for N fertiliser is greatest and potential maximum uptake rates in this type of country. However, further work needs to carried out investigating fertility indices and maximum break even points of N fertiliser application before any viable cost effective recommendations of N fertiliser application can be made. The information does show though, that the potential for N fertiliser is far greater than present and conventional application rates.

6.5 CONCLUSIONS

The pasture growth data presented above highlight the findings of Moir (2000) that pasture growth is affected by a number of climatic and soil fertility factors. However, in hill country these factors are compounded by the varying aspects and slopes, which in themselves provide variations in fertility and climate. These variations lead to a wide range of pasture growth rates throughout the year and provide interesting contrasts between aspects, slopes and fertility treatments.

The general pattern of pasture production is that at the start of autumn, all sites produce a reasonable level of pasture growth. However, due to falling energy inputs in late autumn and winter, pasture growth becomes limited on the southerly and flat aspects, while the northerly aspects retain a relatively high growth rate. The advent of spring boosts pasture growth on all sites due to increased energy inputs and a "spring flush" of available nutrients. The exceptions are the NS sites which become limited by soil moisture. The soil moisture limitation effects the NE sites later in spring and continues throughout summer, unless there is adequate rainfall. The southerly and flat sites continue producing good growth rates throughout spring and summer due to higher soil moisture levels, and don't become restricted by moisture until the end of summer.

A similar pattern is found in the degree to which pasture production is limited by N availability. The only variation is that the NS sites have a comparatively higher level of pasture yield depression than the other sites in winter. This is likely to be due to the chronic N deficiency on these sites becoming more apparent in winter when the sites are provided with adequate soil moisture and energy inputs to provide relatively unrestricted growth.

The lack of clover on this type of country is highlighted by the clover growth data. Clover growth was present on only a few sites throughout the trial period and in low quantities. The increased P fertility had a significant effect in increasing total clover growth, however it was only statistically significant in few of the individual growth periods.

Nitrogen fertiliser application did not appear to have a significant effect in decreasing clover growth in terms of total growth or in individual periods. The overall lack of clover growth can be put down to the dry nature of the country which becomes basically void of clover growth during drought periods. It therefore, takes a long time for the clover to regenerate to adequate levels, by which time another dry period occurs. The general lack of clover growth provides a sound understanding as to why this type of country is so deficient in N and why this type of research is so relevant.

The increased P fertility on the HP sites appeared to only have a minor effect in increasing pasture production in each of the individual growth periods - with the largest effect appearing during dry periods when the increased pasture cover and deeper rooting depth of the HP pasture provided greater growth and N response later into the dry spell. The NE and flat sites provide a consistent P response throughout much of the year on non-limiting N sites. This is likely to be due to the development of a P deficiency (as a result of overall higher growth rates), which is overcome on HP sites. Overall the high P sites produced significantly more pasture than the LP sites. However, the increase is small in comparison to the N response and the lack of clover growth must question the value of large P applications as opposed to N applications.

Due to a number of reasons, including the lack of clover growth, the Olsen P test was found to be a poor overall indicator of potential pasture yields. The mineralisable N test however, showed some potential as an indicator of soil N status and subsequent pasture yield. The test however, is limited by the fact that it is carried out under standard temperature conditions within a laboratory. In the field though, soil temperature regimes vary greatly between slopes and aspects, and as a consequence the actual mineralisation rates between the sites varies as well. Consequently the test is limited by fluctuating soil temperature regimes in the field, which also limits its applicability for use as a pasture growth indicator.

The results overall suggest that the potential for N fertiliser application on dry hill country is high, with potential responses up to high rates of N application. The potential for northerly aspects is highest from autumn through to the beginning of spring, while on southerly and flat aspects it is greatest from early spring through to early summer. To take advantage of these varying response periods for differing aspects, there needs to be some advances in fertiliser spreading technology, and a willingness by farmers to alter their fertiliser application practices. There also needs to be more work carried out investigating response curves and developing fertility indices for this type of land.

Plate 6.1 The effect of N fertiliser on a LPSE site in late autumn. The N added plot is in the fore ground.

Plate 6.2 Pasture growth on a HPNE site in late autumn with N fertiliser added.

Plate 6.3 Pasture growth on a HPNE site in late autumn without N fertiliser.

CHAPTER 7

PASTURE GROWTH MODELING

7.1 INTRODUCTION

There has been considerable investigation of pastoral fertiliser responses on a range of soils and landscapes. A common feature pervading this work is the large variability in dry matter response, even when soil tests are similar. This variability is largely a consequence of climatic variability. Yet, despite its obvious importance, the effect of climate on fertiliser responses is rarely taken into account. Evidence of this lack of use of climatic data was given by Grandar and Kerr (1980). They examined 100 papers reporting on agronomic field trials in New Zealand, and reported that "climatic and soil data were rarely used to aid interpretation of results". Moir *et al.* (2000) commented that there is little evidence in the scientific literature to suggest that the situation has changed in the last 20 years.

In an attempt to overcome the effect of climate, most studies express the fertiliser response in terms of relative yield. A major problem with this method however, is that relative yields do not allow a quantitative prediction of dry matter production unless there is an accurate measure of potential yield – a condition not often met. Without quantitative predictions of pasture response it is impossible to develop "decision support" fertiliser models which allow whole farm system modeling and economic analysis. There is therefore, a need to develop a method which can give a quantitative prediction of dry matter yield rather than a relative prediction.

One approach to predicting the separate effects of climate and soil fertility on dry matter yield has been developed recently in two studies by Faulalo (1997) and Moir *et al.* (2000). They suggested that consideration of evapotranspiration (E_t) may be a useful way of combining the varying climatic parameters (soil water availability and energy inputs) into a single factor that can broadly summarise the effect of climate. Both studies investigated pasture growth and fertiliser response relative to E_t and found a good relationship between pasture growth and soil fertility when growth was expressed per mm of E_t. Therefore, by isolating the climatic effect on pasture growth it allows growth to be estimated quantitatively rather than relatively. This opens the door for the development of a new generation of pasture growth models which can predict pasture growth and fertiliser response quantitatively.

Both studies mentioned above calculated pasture growth on flat land. The pasture growth data presented in Chapter 6 provide an opportunity under unlimiting nutrient (P & N) conditions to model the impact of a whole range of microclimates (caused by slope and aspect) on E_t and pasture growth. Therefore, this chapter examines the scope for further developing the approach used by Faulalo (1997) and Moir *et al.* (2000).

If a model is able to isolate whether constraints on pasture growth are largely climatic or fertility based, the potential benefits to future farming practices are large. Environmental and financial constraints mean that fertiliser needs to be applied in the most effective, beneficial and "safe" manner possible. This means that fertiliser should be applied at the right rate and correct time so that minimal losses are incurred and maximum production gains are achieved. Isolating the major constraints for varying aspects, slopes and more generally, regions, allows fertiliser recommendations to take into account whether fertiliser applications will be maximised or whether the risk of loss and pollution is increased.

7.2 MODEL DEVELOPMENT

This model relies on three major assumptions-

- That one variable, E_t, can encompass the most important climatic parameters affecting pasture growth. This may not be unreasonable given that E_t depends on the input of solar energy, the temperature and the availability of soil water.
- That the assertion of McAneney and Judd (1983) that "to an acceptable first approximation, dry matter production is proportional to transpiration" is true.

- That the assertion of Kerr *et al.,* (1986) and Allen *et al.,* (1998) that for full cover pasture (LAI > 3), nearly all of evapotranspiration is transpiration, is true.

The basic model is described here, and is justified in a later section. Pasture growth *(G)* is calculated daily. It is assumed to be proportional to the actual evaporation rate (*E*) so that

$$G = kE \text{ if } kE > 0 \text{ else } G = 0 \tag{7.1}$$

The conditional statement in Eq. (7.1) is included to avoid the prediction of negative growth on the odd day that the net radiation is slightly negative.

A number of studies have shown linear relationships between evapotranspiration and pasture production. In addition to the work of McAneney and Judd (1983) mentioned above, other workers who have made similar claims include Rickard and Fitzgerald (1970), Wright and Baars (1976) and Rickard *et al.* (1986).

The proportionality constant (*k*), with units of kg D.M./ha/mm, is a site-specific factor which could be an index of soil fertility status. Ritchie (1983) and Power (1983) showed that *k* is proportional to soil fertility, unless the pasture is sparse and the exposed soil surface is dry. Tanner and Sinclair (1983) argued the opposite, that unless malnutrition is severe, *k* is not greatly affected by nutrient status as E_t is reduced in less fertile soils due to less transpiration. Therefore, the lower pasture growth rate in less fertile soils was assumed to be a result of less transpiration rather than less efficient E_t. It is argued in this thesis that *k* is a function of soil fertility. To test this assertion pasture growth under unlimiting nutrient conditions is used to calculate *k* and test the model's validity.

7.2.1 Calculation of E_t

Evaporation is calculated as described in Moir *et al.* (2000) but modified to take into account the effect of aspect and slope. The model is computed on an Excel worksheet and all angles and latitudes are in radians.

The simple soil water balance used to estimate E_t is that described by Coulter (1973b). When the plant root zone is at field capacity, it is assumed to hold a certain maximum amount of plant-available water (W_a). If there is plant available-water (W) in the root-zone, E is assumed to occur at the reference crop or potential E_p rate. Once the available water is fully used, E_t is assumed to be zero. Excess water is assumed to be lost as deep drainage or surface runoff if, and only if, the available soil water has been recharged to W_a.

Processes such as surface runoff induced by compaction, water repellency or steepness of slope, are not included in the model as sufficient information about their effects is not currently available.

The following equations describe the water balance. Writing the plant-available water stored in the root zone at the conclusion of day j as W_j, then

$$W_j = W_{j-1} + P - E - D \tag{7.2}$$

where P is the rainfall. On sloping ground $P = P_f \cos(s)$ where P_f is the rainfall on a horizontal surface and s is the slope. E is the evaporation, and D is the drainage (including surface runoff), all on day j, and W_{j-1} is the value of W at the end of the preceding day. All the terms in Equation (6.2) are equivalent water depths. E is found as

$$E = E_t \text{ if } W_{j-1} + P \geq E_p \text{ else } E = W_{j-1} + P, \tag{7.3}$$

where E_p is the estimate of reference crop evaporation for day j, calculated as described below. D for day j is found as

$$D = W_{j-1} + P - E - W_a \text{ if } W_{j-1} + P - E > W_a \text{ else } D = 0. \tag{7.4}$$

$$W_a = (\theta_{fc} - \theta_{pwp})\, d \tag{7.5}$$

where θ_{fc} is the volumetric water content at field capacity, θ_{pwp} is the volumetric water content at permanent wilting point and d, is the effective depth of the root zone.

Equations (7.2), (7.3) and (7.4) ensure that $0 \leq W \leq W_a$.

The Priestley and Taylor (1972) formula (Eq. 7.6) can be considered as a simplified version of the Penman (1948) formula. It however, uses fewer parameters to estimate E_p and has been shown to be just as accurate as the Penman (1948) equation in the Manawatu (Clothier *et al.,* 1982). It is therefore, the preferred means by which to estimate E_p. The equation can be written as

$$E_p = (1.26\, s\, R_n)/[\rho_w\, L\, (s + \gamma)] \tag{7.6}$$

where s is the slope of the relationship between the saturated vapour density and temperature, γ is the psychrometric constant, R_n is the net radiation over the 24 hour period (MJ/m^2), ρ_w is the density of water (1000 kg/m^3), and L is the latent heat of vaporisation of water at ambient temperature (2.5 MJ/kg). A quadratic equation fitted to tabulated values for the dimensionless ratio of $s/(s + \gamma)$ (Tanner pers. comm.) at an air pressure of 100 kPa over the temperature ranges 5 to 20° C gives

$$s/(s + \gamma) = 0.403 + 0.0164\, T_{av} - 0.00012 T_{av}^2 \tag{7.7}$$

where T_{av} (°C) is the average screen air temperature, approximated as the mean of the daily maximum and minimum. The net radiation may be estimated from the daily incoming solar radiation (R_s) (Scotter *et al.,* 1979) as

$$R_n = 0.62 R_s - 1.47, \tag{7.8}$$

where both R_n and R_s are in units of MJ/m^2. For sloping surface the solar radiation is calculated by

$$R_s = R_m\, [(1 - R_d)\, R_f + R_d \cos(S)] \tag{7.9}$$

where R_m is the measured horizontal surface solar radiation and S is the slope in radians. If solar radiation data are not available, values can be estimated from sunshine hour data for the day, as described by Scotter *et al.*, (2000). R_f is the ratio of the direct beam radiation for a sloping surface to a flat surface, which is calculated as

$$R_f = a + b\,(\sin(2\pi/365\,J - c)) \qquad (7.10)$$

where slope variables a, b, and c are parameters obtained by fitting a sine wave to the values given for a certain slope and aspect by McAneney and Noble (1976), (values for a, b and c can be found in Appendix 1), and J is the julian day. R_d is the fraction of incoming surface radiation that is diffuse which is calculated on the premise that on a completely cloudy day all of the radiation is diffuse, whilst on a sunny day only 10 % of the radiation is diffuse (Robinson, 1966) and is estimated by

$$R_d = 1 - 0.9\,(n/N) \qquad (7.11)$$

where n is the measured sunshine hours, and N is the maximum measurable sunshine hours in that day. N is calculated as

$$N = 24\cos^{-1}(-\tan\varphi \tan\delta)/\pi - 0.5 \quad \text{(Sellers, 1965)} \qquad (7.12)$$

where φ is the latitude, and δ is the solar angle of declination, which is calculated by

$$\delta = 0.41\sin[(J - 79)\,2\,\pi/365] \quad \text{(Rosenberg, 1974)} \qquad (7.13)$$

The 0.5 in Eq. (7.12) is to take into account the variability of the sunshine hour recorder to register at low sun angles.

The model can also estimate the gravimetric water content (ω_m). This can be used to validate the model against measured values. ω_m is calculated as

$$\omega_m = (W\rho_w / \rho_b / d + \omega_{pwp}) \tag{7.14}$$

where ρ_b is the soil bulk density and ω_{pwp} is the gravimetric water content at the permanent wilting point.

The key equation which enables the solar radiation to be calculated on varying slopes and aspects is equation (7.9). It differentiates whether the solar radiation on any given day is mainly beam radiation or diffuse radiation. Table 7.1 gives a good indication of the variance in solar radiation for different slopes (0 and 30°) and aspects (north and south) during the year as calculated by equation (7.9). Four days were chosen, a sunny day in both mid summer and mid winter and a cloudy day in mid summer and mid winter. The flat site effectively shows the measured solar radiation on each day whilst the NS and SS sites provide extreme contrasts. The first point of note from Table 7.1 is that in winter the NS sites receive almost twice as much radiation as flat sites on a sunny day (15.8 and 8.3 MJ/m^2 respectively) while the SS sites receive next to no radiation (0.4 MJ/m^2). This is a consequence of the sun being lower in the sky, which causes the NS sites to receive more incident radiation than flat sites, with the SS sites receiving direct sunlight for only a short period of time in the middle of the day. On a cloudy day the NS and SS sites receive the same amount of radiation (1.8 MJ/m^2), due to it all being diffuse. This is marginally less than flat sites (2.1 MJ/m^2) due to the effect of slope.

In early summer when the sun is high in the sky, a very different pattern emerges. On a sunny day the flat sites receive the most solar radiation (32.0 MJ/m^2) followed by the SS sites (28.0 MJ/m^2), then the NS sites (26.6 MJ/m^2). The higher sun position and greater number of sunshine hours in the summer is illustrated by the flat sites receiving twice as much radiation in summer as NS sites received in winter on sunny days. The SS sites received more radiation than the NS sites due to the sun's rays coming from a partly southerly direction in the early morning and late afternoon in summer. On a cloudy summer day, the NS and SS sites once again receive the same amount of diffuse radiation (7.6 MJ/m^2). Table (7.1) provides a simple illustration of how the variation in the sun's path throughout the year affects the solar radiation received by varying slopes (0 and 30°) and aspects (north and south) and also shows how cloudiness affects this.

Table 7.1 Calculated sloping solar radiation (MJ/m^2) on varying slopes (0 and 30°) and aspects (north and south) in summer and winter.

	Northerly steep	Southerly steep	Flat
Sunny day winter	15.8	0.4	8.3
Cloudy day winter	1.8	1.8	2.1
Sunny day summer	26.6	28.0	32.0
Cloudy day summer	7.6	7.6	8.8

7.3 DATA FOR MODEL PARAMETERISATION AND VALIDATION

As has already been stressed, the objective of this study was to assess the applicability of the modeling approach developed earlier by Faulalo (1997) and Moir *et al.* (2000) to predicting fertiliser responses in dry hill country.

A key determinant of the utility of such a model is the number of input parameters that are required. These must be as few in number as possible, and all must be readily available to farmers or their advisors.

Climate parameters required for the model include sunshine hours, or solar radiation, daily maximum and minimum temperatures and daily rainfall. Of these, only daily rainfall would be measured routinely by farmers, although the others are measured at various regional stations. The data from these regional weather stations are increasingly available over the internet in a form suitable for direct inclusion in models such as this.

Thus a key check on the utility of this model will be whether regional weather data can be used for many of the input parameters and yet still achieve reasonable levels of prediction at this site.

The model was applied to the soil water and pasture growth data recorded in the Waipawa pasture growth trial (presented in Chapters 5 and 6).

In this study, maximum and minimum temperatures were taken from the Kopua weather station (closest meteorological station to the site), sunshine hours were recorded at Dannevirke , and solar radiation recorded at Napier. (Both stations were the closest that provided the necessary information.)

Rainfall can vary markedly over small distances, and it is therefore necessary to record it on the property. On large hill country properties more than one recording site may be required. In this study rainfall was recorded daily at the site by the staff operating the fertiliser trial.

Slope values used for calculation were 10^0, for easy slopes and 30^0, for steep slopes. These were estimated as being average values for the relevant slope categories.

The sole soil parameter required was the available water holding capacity W_a. This was defined in Eq. 7.5 as

$$W_a = (\theta_{fc} - \theta_{pwp})d$$

where θ_{fc} is the volumetric water content at field capacity, θ_{pwp} is the volumetric water content at permanent wilting point, and d is the effective depth of the root zone.

The simplest scenario would have been to assume that all soils on the trial site (and perhaps elsewhere) have a similar W_a. It was immediately apparent however that such an assumption would lead to major errors in the model.

Previous gravimetric soil water content data recorded at the site showed large differences in the water storage potential of differing sites. This was indicated by varying differentials between the maximum and minimum gravimetric water contents recorded at each site over four years of measurement. Pressure plate data could have been used to calculate accurately the soil water storage potential of the soil. However, because of the necessity to have input parameters that can be obtained as simply as possible it was decided to make use of the abundance of data already collected at the site to calculate W_a.

W_a was therefore estimated from the average maximum gravimetric water content recorded on the sites. The minimum gravimetric water content was estimated from the average yearly minimum value gravimetric soil moisture recorded over the four years of trial operation. The gravimetric data were converted to volumetric values using bulk density values measured by the AgResearch staff. Initial runs of the model assumed a uniform rooting depth (d) from which available water could be obtained of 75 mm.

Very early in the model development it became apparent that predicted rates of E_t on NS sites greatly exceeded actual rates. Inspection of these sites revealed that a key assumption of the model, namely complete pasture cover – was not appropriate on these areas. Throughout the year, bare ground appeared to comprise 10-50 % of the area due to the dry nature of these sites. McAneney *et al.* (1982) found that bare ground reduced the evaporation rate from pastures with low leaf area indexes, and stated that "evaporation from the bare soil can be neglected in evapotranspiration models". The model was therefore adjusted so that E_t on NS sites was 67 % of the rate calculated assuming full pasture cover. Woodward *et al.* (2001) used a similar adjustment for calculating soil water deficit on pasture in Dunedin where bare ground was found to be a factor affecting pasture water usage.

Although it was disappointing so early in the model development to need to make an arbitrary correction to the "global" assumptions in the model, this is a correction that perhaps could be made on a regional basis and would not need to be independently assessed at each site.

7.4 MODEL EVALUATION

As has been indicated previously, pasture growth rates are determined by a complex interaction of environmental parameters and soil nutrient supply. Earlier, a number of authors had suggested that pasture growth rate is linearly related to evapotranspiration by a proportionality constant (*k*) that is a function of soil fertility. This concept is the basis of the model described in Section 7.2.

Evaluation of this central concept in the model is complicated however, by the extreme difficulty in actually measuring the rate of evapotranspiration in hill country pastures. Estimates of evapotranspiration must be made by indirect means. Thus, when the pasture growth model is evaluated, it is difficult to assess whether differences between predicted and measured growth rates indicate that growth rate is not in fact linearly related to evapotranspiration, or simply reflect errors in the estimate of evapotranspiration.

Although this presents a logical difficulty, the distinction is less important when the utility of the model is considered. If the model is to be useful it must be able to estimate evapotranspiration from simple input parameters. If this cannot be done, then whether or not pasture growth is actually proportional to evaporation becomes something of an academic question.

The evaluation of the model was conducted in three stages.

- The ability of the model to estimate evapotranspiration over a range of slopes and aspects was assessed indirectly by comparing predicted gravimetric soil water contents with measured values.
- The calculated annual values of evapotranspiration at each site were then used, together with annual pasture production at those sites, to calculate an individual proportionality constant (*k*) for each site. This value was then used to predict pasture growth rates, on a cut-by-cut basis at each site, and the predicted and measured values compared.

- The performance of the model across a range of slopes and aspects was assessed by assuming that the plus-N plots all had non-limiting soil fertility, and should therefore have had the same proportionality constant (*k*). An average value for *k* was therefore calculated for all the plus-N plots, and this value used to compute seasonal and annual pasture production on all slopes and aspects. These calculated data were then compared with measured values.

7.4.1 Gravimetric soil moisture validation

7.4.1.1 Gravimetric soil water content 1996-99

Gravimetric soil water content has been measured at the Waipawa fertiliser trial on a regular basis since 1994 on NE, NS, SE and SS sites. As a means of testing the model's ability to predict soil water content, climate data for the period of January 1996 to December of 1999 were entered into the model to compare predicted gravimetric soil moistures with measured values. Figures 7.1, 7.2, 7.3 and 7.4 show the comparisons for NE, NS, SE and SS sites. As a whole, the model predicted the gravimetric soil moistures well. The pattern of measured values is followed by the predicted values very well, with maximum and minimum values closely predicted on most treatments.

The exceptions are:-

- The measured values dropped below the minimum gravimetric water content on the northerly slopes, which is due to the model's minimum value for soil water content being set too high.
- The model over-predicted soil moisture levels in the winter of 1998. This period followed a long drought which stretched from October 1997 to May 1998. This extended dry spell appeared to have some effect on the soil's ability to rewet to field capacity once the drought was broken. This was possibly a result of hydrophobicity, which as mentioned above, is not able to be compensated for at the present time.
- The model overestimated the rate at which the SS sites rewet to field capacity. Possible reasons for this will be discussed later.

It must be noted however, that a model of this type can be extremely "volatile" in terms of its accuracy for two main reasons. Firstly, the soil water content can drop from field capacity to permanent wilting point (PWP) in a matter of 2-3 days, and conversely rise from PWP to field capacity in one day (if sufficient rainfall occurs). Therefore, the timing of soil sampling can be crucial to the apparent accuracy of the model. If for instance, a soil sample is taken in the morning when it is dry, and it rains in the afternoon, the model, which is based on daily rainfall will predict that the gravimetric soil moisture on that day will be high, whereas the measured value may be low.

Secondly, the model predicted that soil water is readily available for evapotranspiration down to the PWP (i.e. soil water is either available or unavailable). In reality, water availability is likely to become limited before the gravimetric soil water reaches the PWP (McAneney and Judd, 1983). Considering these simplifications, the model predicted well the gravimetric soil moistures on NE, NS, SE and SS sites over the period of four years.

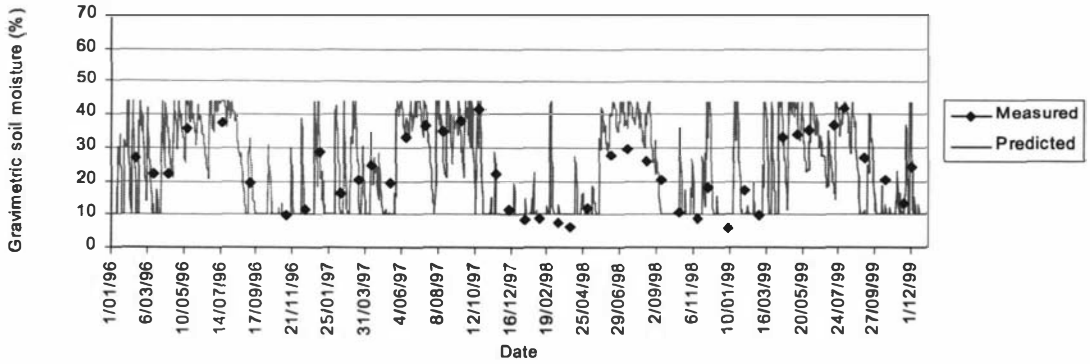


Figure 7.1 Measured and predicted gravimetric soil moisture content for the NE sites from 1996-1999.

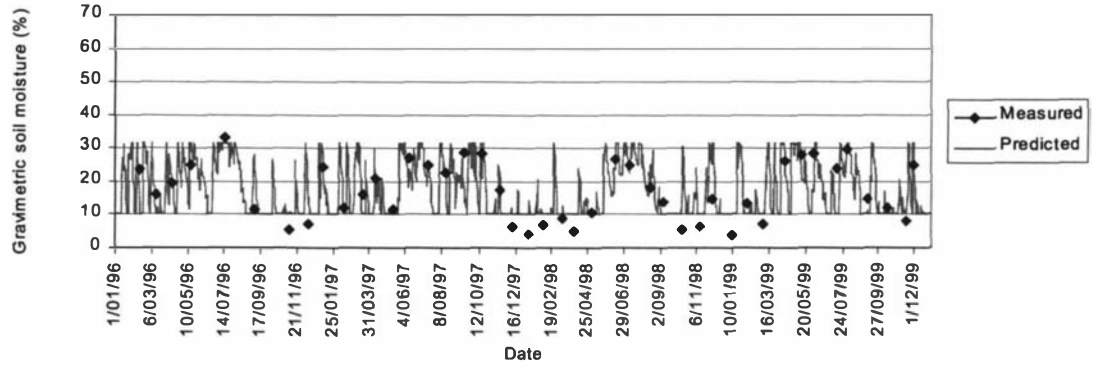


Figure 7.2 Measured and predicted gravimetric soil moisture content for the NS sites from 1996-1999.

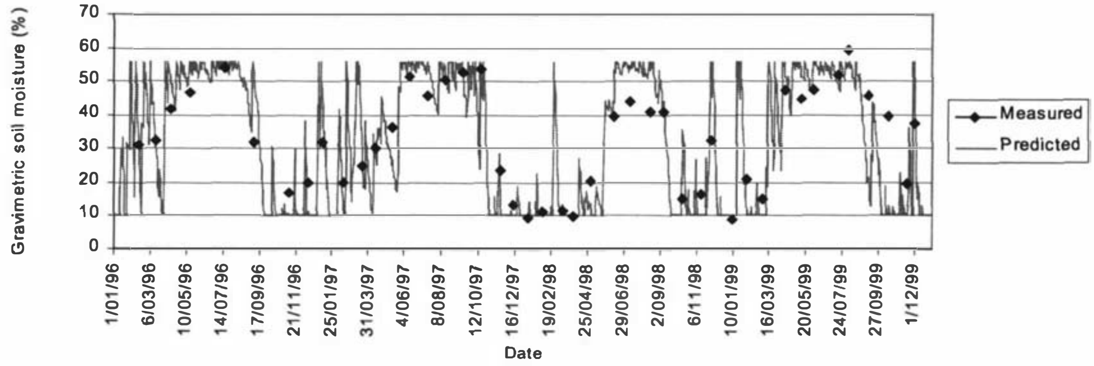


Figure 7.3 Measured and predicted gravimetric soil moisture content for the SE sites from 1996-1999.

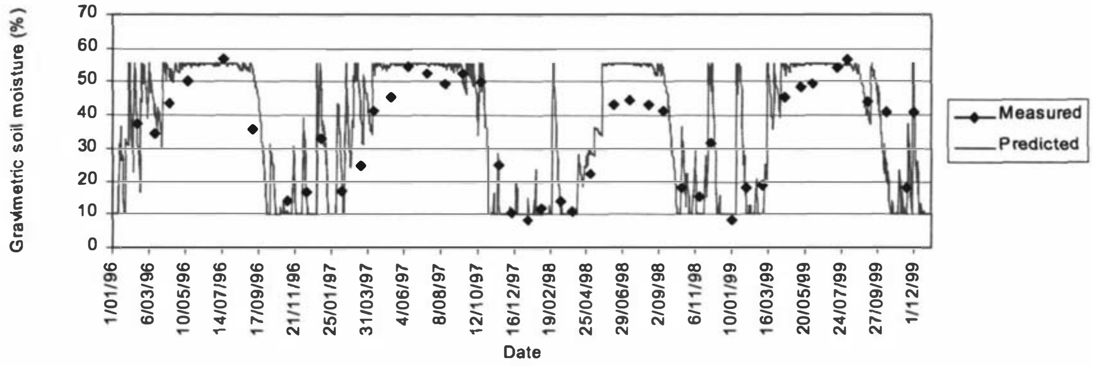


Figure 7.4 Measured and predicted gravimetric soil moisture content for the SS sites from 1996-1999.

7.4.1.2 Gravimetric soil water content for the trial period

The gravimetric soil water contents for the NE sites (Figure 7.5) are predicted reasonably well by the model throughout the trial period. Although a couple of the measured values do not totally agree with the predicted values, the discrepancies were usually small.

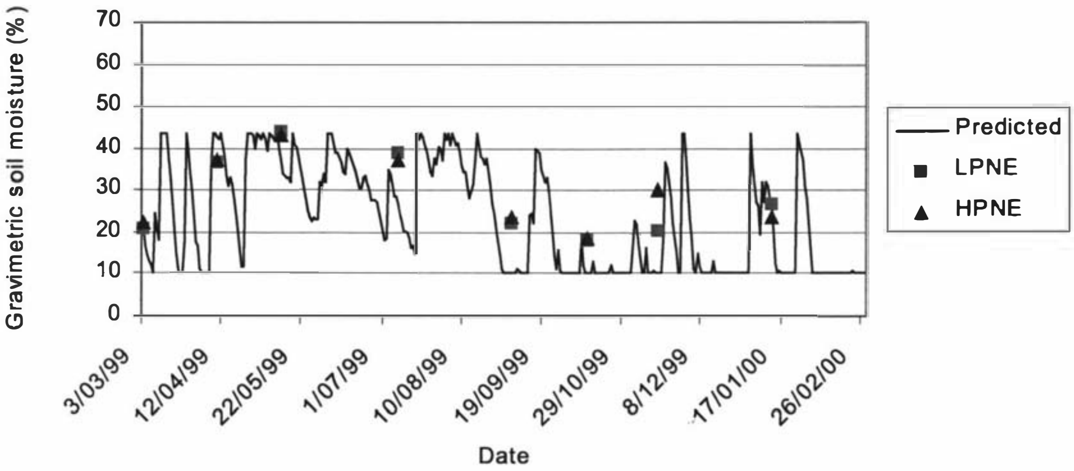


Figure 7.5 Measured and predicted gravimetric soil moisture for the NE sites.

There was good agreement between measured and predicted gravimetric soil water contents for the NS sites (Figure 7.6). Of note for the NS sites are the more frequent fluctuations in the predicted values away from FC during winter. This is due to the lower water holding capacity of the soil on these sites, which means that the predicted gravimetric soil moisture fluctuated between field capacity and permanent wilting point more often than on other sites with higher water holding capacities.

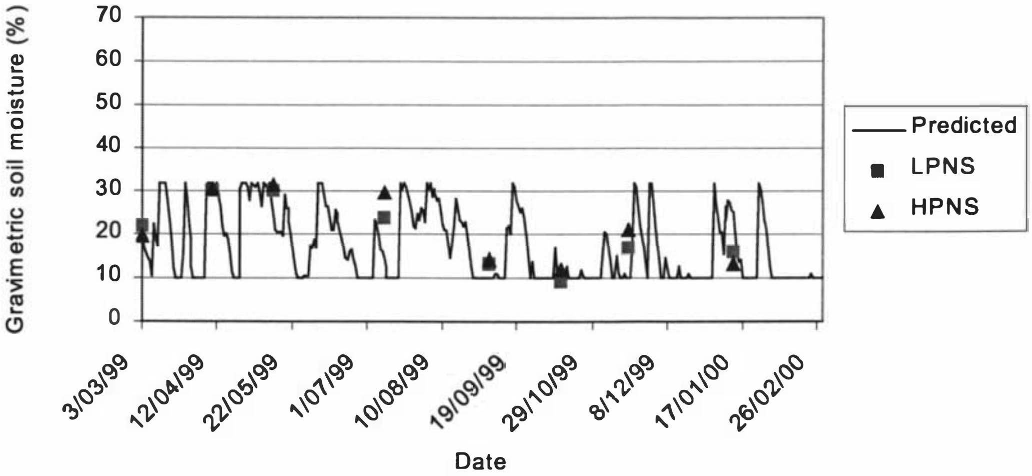


Figure 7.6 Measured and predicted gravimetric soil moisture for the NS sites.

The model did a reasonable job of predicting the general pattern of soil moisture throughout the year on the SE sites (Figure 7.7). However, the model predicted that the soil dried out more quickly during spring than was measured. This may be due to the assumption that soil water is either available or unavailable whereas, in reality, as the soil moisture approaches PWP it becomes harder for the pasture to extract. This effect is likely to be more pronounced on southerly slopes with a higher organic matter content. Due to the surface charge on organic matter, water can be held more tightly in soils with a higher organic matter content (McLaren and Cameron, 1990). Therefore, in the spring when the model assumes that the soil has reached the PWP there is still likely to be water in the soil which is not readily available for evaporation.

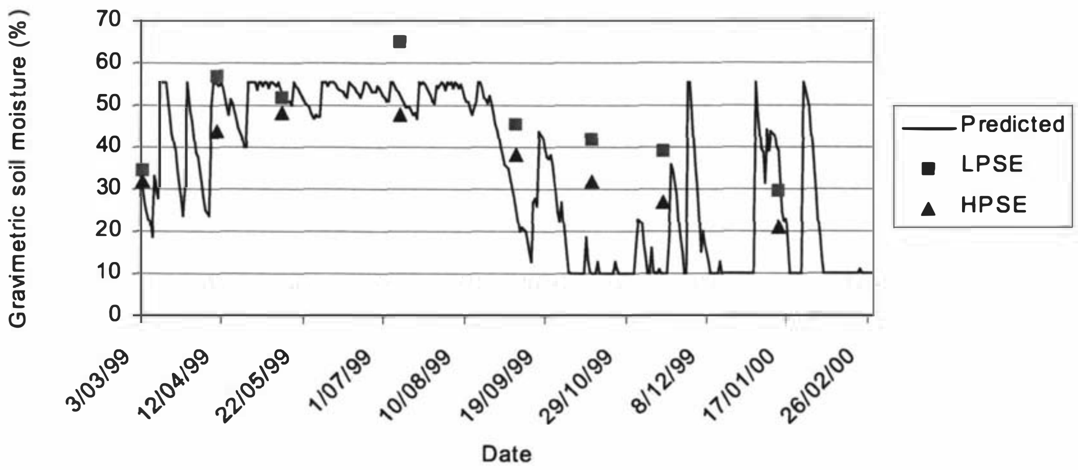


Figure 7.7 Measured and predicted gravimetric soil moisture for the SE sites.

Figure (7.8) shows that the model predicted the gravimetric soil water content of SS sites reasonably well until mid to late summer, at which time it over predicted the gravimetric soil moisture. A possible explanation for this is that during summer soil on the southerly slopes, may have become hydrophobic when it became dry. Thus, rainfall after dry spells did not infiltrate the soil as effectively and soil moistures did not increase as much as predicted. The effect may be more pronounced on the southerly slopes as hydrophobicity is greater on soils with higher organic matter levels (Marshall *et al.,* 1999). It should be noted however, that no assessments of hydrophobicity were made in this study.

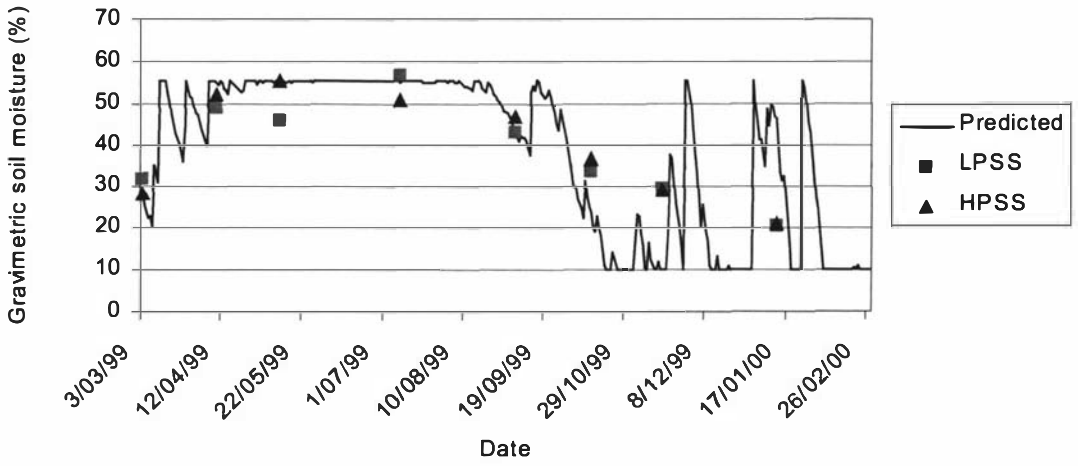


Figure 7.8 Measured and predicted gravimetric soil moistures for the SS sites.

The gravimetric soil water content results for the flat sites (Figure 7.9), show that the model under-predicted moisture levels in the spring and over-predicted soil moisture at the end of summer. As with the SE and SS sites these deviations of predicted values from measured values are likely to be due to water being bound more tightly to the soil than the model predicts in spring and the development of hydrophobicity in summer. Overall though, there was a reasonably good agreement between the measured and predicted gravimetric soil moisture values for flat sites over the trial period.

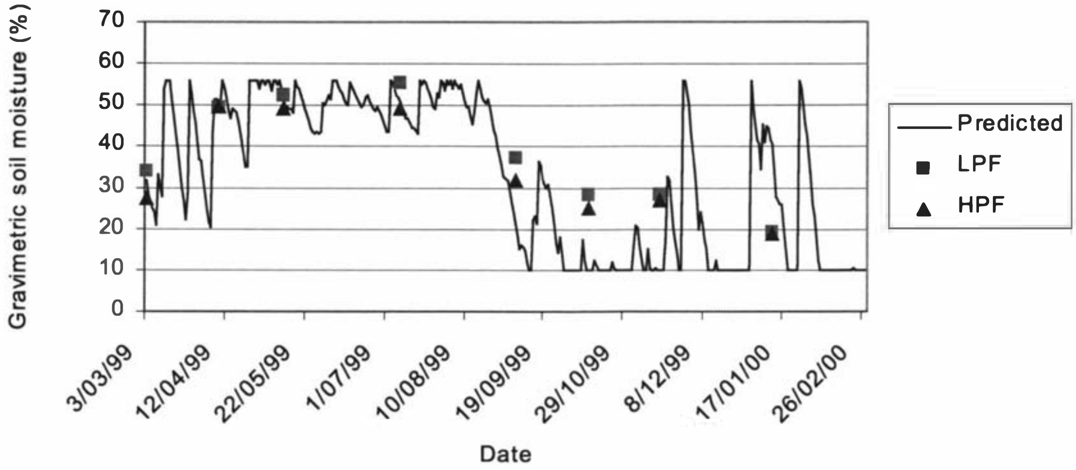


Figure 7.9 Measured and predicted gravimetric soil moistures for the flat sites.

In summary therefore, this simple model, with a minimum of input parameters, appears to do a reasonable job of predicting soil water contents across a range of slopes and aspects at the dry hill country trial site. This is the first step in modeling pasture production on these sites.

7.4.2 Prediction of pasture growth rates at individual sites

In Table 7.2, the estimates of annual evapotranspiration are presented for each of the landscape units. These vary from 314 mm on the NS sites to 545 mm on the flat sites. The lower evapotranspiration (once adjustments have been made to account for bare ground) from the NS sites reflects reduced rainfall inputs per unit area, due to the slope of the land, and a lower water holding capacity which means that a higher proportion of rainfall goes to deep drainage.

The rainfall at the site, over the year-long duration of the trial was 862 mm. On the flat sites therefore, deep drainage amounted to 337 mm, or 39 % of rainfall. On the NS sites, after allowing for slope, 420 mm (56 % of rainfall) was lost to deep drainage or surface runoff to other sites.

If pasture production is proportional to evapotranspiration then these data suggest a range in potential production of 74 % from lowest to highest sites.

Table 7.2 Table showing the total growth of LP and HP sites (non-limiting N), the calculated total E_t and calculated *k* values.

Treatment	Total growth (kg D.M./ha)		Total evap (mm)	Calculated *k*	
	LP	HP		LP	HP
NE	14397	18629	515	28.3	36.6
NS	8271	9755	314	26.3	31
SE	11900	12270	474	25.4	26.2
SS	8995	11184	347	25.9	32.2
Flat	12768	15810	545	23.8	29.4
Mean	**11266**	**13530**	**439**	**25.9**	**31.1**

Even more variable are the daily evapotranspiration rates. These are presented in Figure 7.10A-C for three of the landscape units. If the assumption that pasture growth is proportional to evapotranspiration holds true, then the Figures should represent the relative pattern of pasture growth throughout the year on each site. Obvious features are the erratic evapotranspiration rates on all sites, particularly the NS sites over summer due to lack of soil water, and low values of evapotranspiration on SS and flat sites in winter, due to low levels of incident radiation. The evapotranspiration rates on the northerly sites do not decline as much as on the other sites over this period.

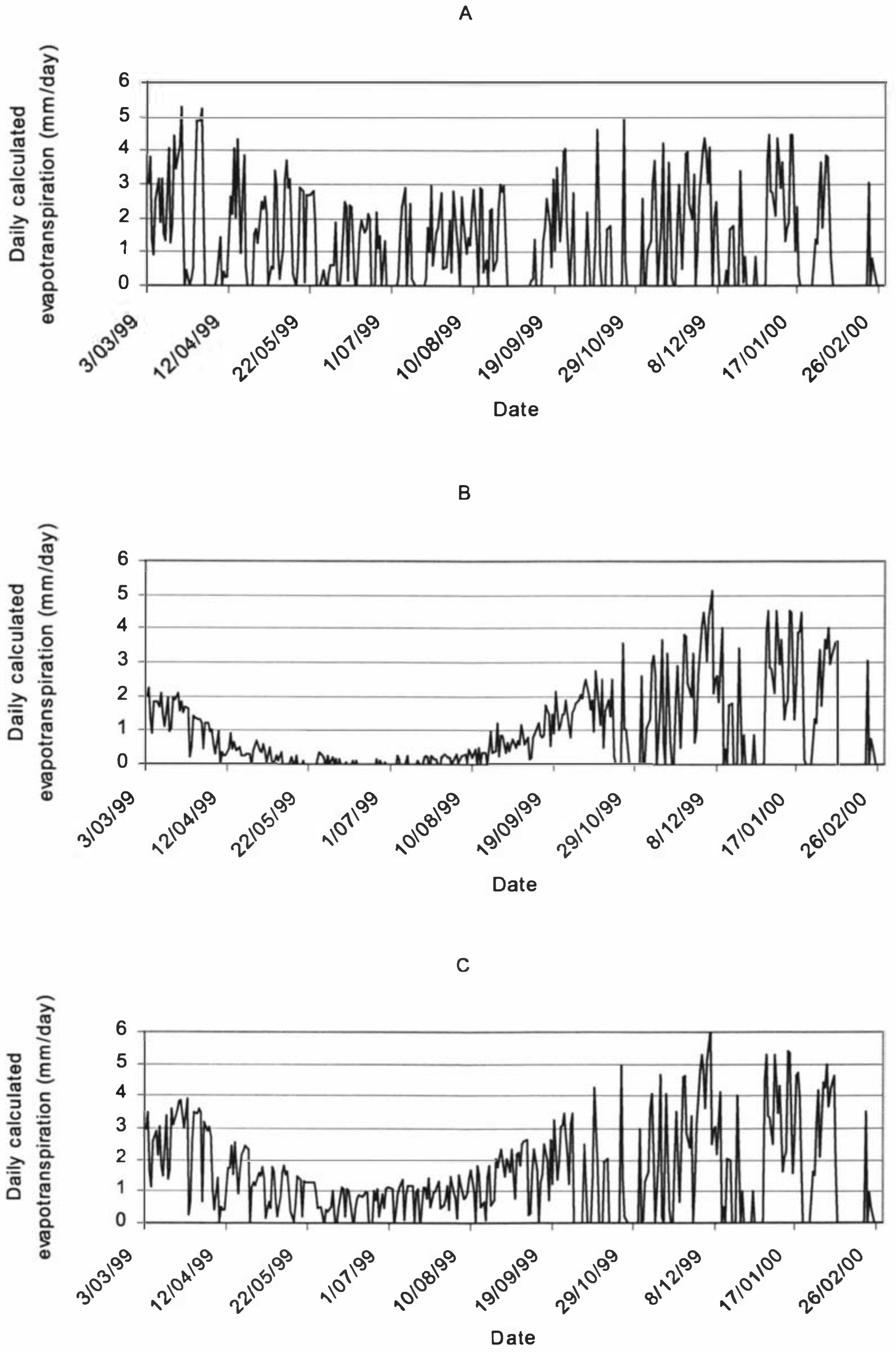


Figure 7.10 Daily calculated evapotranspiration rates for NS (A), SS (B) and flat (C) sites throughout the period of the trial.

As has been stated earlier, the model assumes that pasture production is linearly related to evapotranspiration, with the proportionality constant (*k*) being a measure of soil fertility. If this is indeed the case, and the model provides an accurate measure of actual evapotranspiration, then an estimate of *k* for each site can be obtained by dividing pasture production by the calculated evapotranspiration.

The values of *k* calculated in this way for the sites receiving non-limiting N are presented in Table7.2. These *k* values were used, together with the estimated evapotranspiration rates, to calculate average daily pasture growth rates for each growth period, and the data compared with measured values (Fig 7.11).

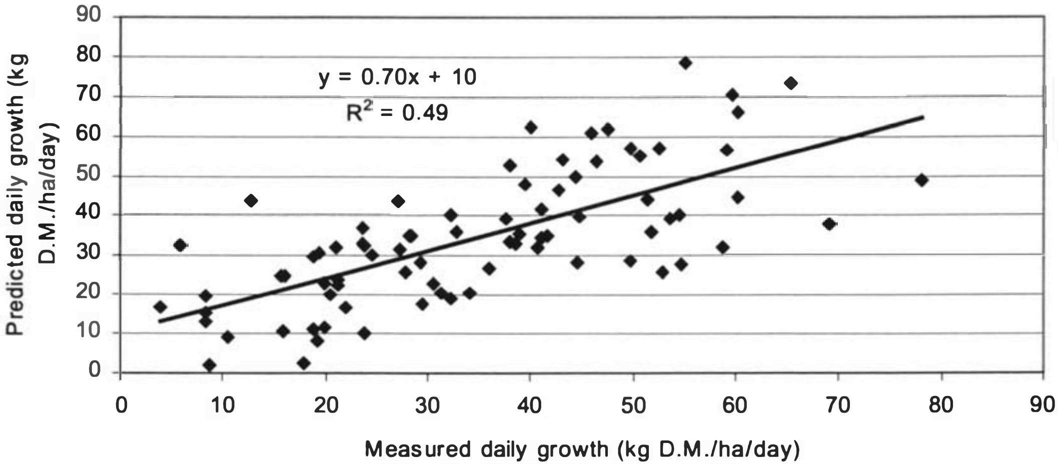


Figure 7.11 Relationship between measured and predicted daily growth rates for unlimiting-N sites, averaged for the 8 growth periods when individually calculated *k* values for each site are used. Marked points are discussed in more detail in the text.

There is a reasonable linear relationship, with the model able to predict approximately 50% of the variation in observed growth rates over the range of slopes and aspects on the trial area.

More detailed inspection of the data, reveals that the variation between predicted and observed pasture growth rates is not random. To illustrate this point, four outlying points are considered in more detail. These are identified in Figure 7.11. For two of the points, the measured daily growth rates greatly exceed the predicted values. These points are towards the bottom right hand corner of Figure 7.11. These data points both relate to the same growth period in early spring on the HPNE and LPNE sites. In this growth period the model predicted that growth would be restricted on these sites by a developing moisture deficit. Clearly this was not the case – perhaps because the pasture was able to access water from a depth greater than 75 mm (unchecked).

Figures 7.12 & 7.13 present predicted against measured pasture growth rates for these two (HPNE & LPNE) sites separately, with the outlying points clearly evident on the right-hand side of each graph. When these outlying points are removed from the regressions the straight-line relationships improve markedly. For the HPNE sites (Figure 7.12) the R^2 value increases from 0.23 to 0.76 (regression not shown). And for the LPNE sites (Figure 7.13) the R^2 value increases from 0.34 to 0.70 (regression not shown).

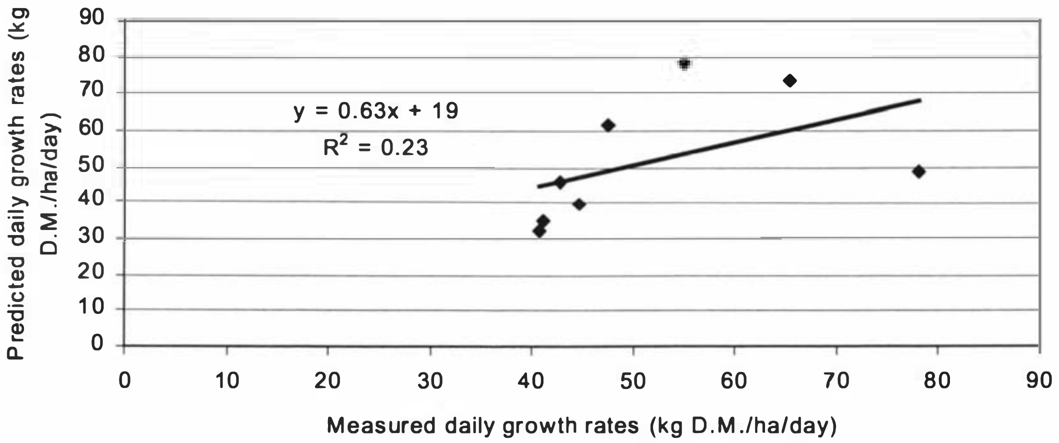


Figure 7.12 Relationship between measured and predicted daily growth rates for HPNE unlimiting-N sites, averaged for the 8 growth periods when an individual calculated *k* value was used.

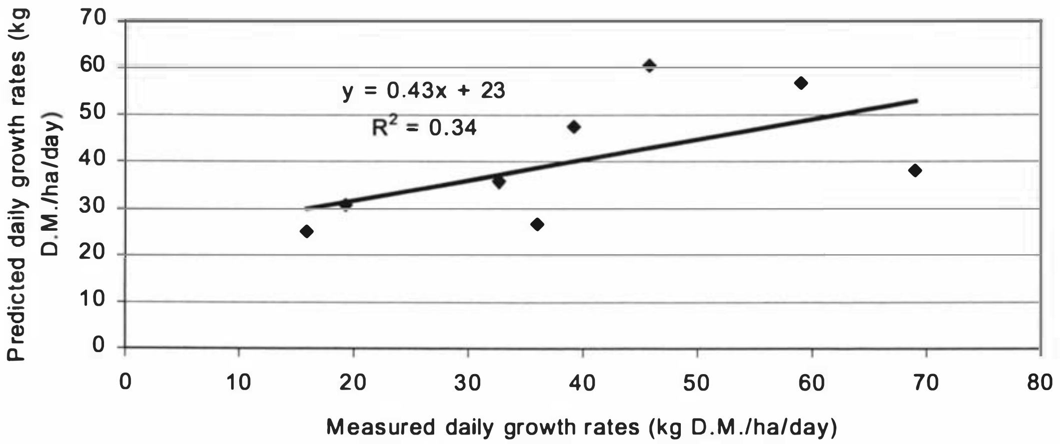


Figure 7.13 Relationship between measured and predicted daily growth rates for LPNE unlimiting-N sites, averaged for the 8 growth periods when an individual calculated *k* value was used.

The other two outlying points in Figure 7.11 occurred when the measured growth rates were low but the predicted growth rates were quite high. These two circled points are marked in the top left-hand corner of the scatter of points in Fig 7.11.

Once again, these two outlying points relate to the same growth period, however this time in late summer. Although this time of year is normally very dry, in the year in which this study was conducted there were reasonably frequent rainfalls over this period. Climatic conditions over this period were such that potential E_t is high. The model therefore predicted that this summer rainfall would be translated into evapotranspiration and consequently high rates of pasture growth. This was clearly not the case. It seems likely that at some locations throughout the trial area, the infiltration of summer rainfall into the soil may not have been very effective – perhaps as a result of hydrophobicity. This would have led to a variable proportion of this summer rainfall being lost in surface runoff, rather than being available for plant uptake.

Figures 7.14 and 7.15 present predicted and measured pasture growth rates for the same two sites (LPSS and LPF). The outlying points are evident towards the top left-hand corner of each graph. If these two outlying points are omitted from the regressions then once again the straight-line relationships are improved greatly. For the LPSS sites (Figure 7.14) the R^2 value increases from 0.43 to 0.84 (regression not shown). For the LPF sites (Figure 7.15) the R^2 value increases from 0.12 to 0.34 (regression not shown).

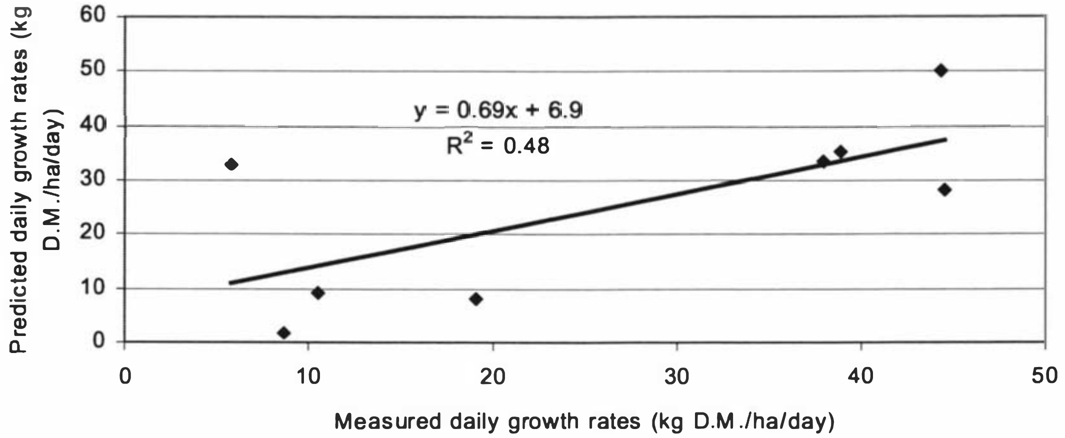


Figure 7.14 Relationship between measured and predicted daily growth rates for LPSE unlimiting-N sites, averaged for the 8 growth periods when an individual calculated *k* value was used.

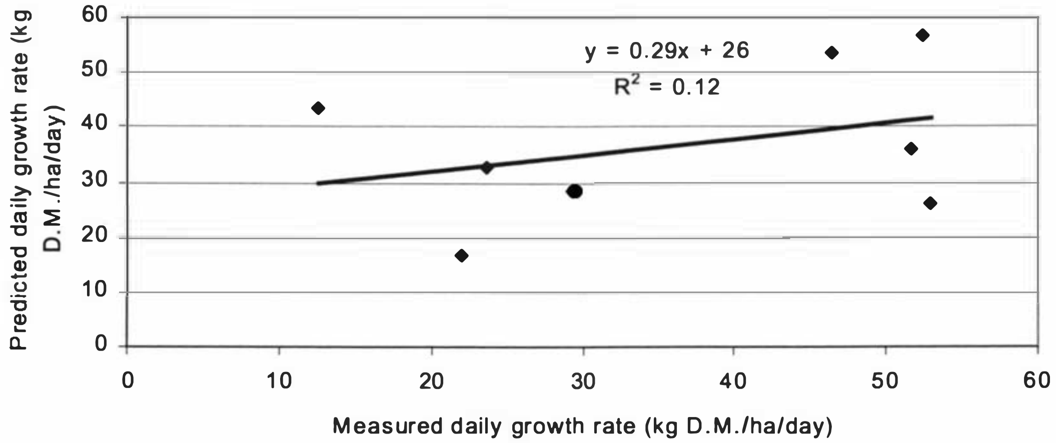


Figure 7.15 Relationship between measured and predicted daily growth rates for LPF unlimiting-N sites, averaged for the 8 growth periods when an individual calculated *k* value was used.

When these four outlying points are omitted from the combined regression analysis of predicted against measured pasture growth rates in Figure 7.11 the R^2 value increases from 0.49 to 0.57 (regression not shown).

In summary therefore, the model in its simplest form can explain approximately 50% of the variation in pasture growth rates at individual sites throughout the year. A preliminary examination of some of the most obvious outlying data points suggests that there may be readily-understandable reasons for the differences between predicted and measured pasture growth rates on some occasions. These reasons will be discussed in more detail later in the chapter, and the possibilities of improving the model predictions, without making the model unacceptably complex, or site specific will be assessed.

7.4.2.1 Predicted pasture production across sites

In the previous section, seasonal pasture production was predicted for individual sites once a *k* value had been derived from measured annual pasture production and calculated annual evapotranspiration at that site. This is a useful start, but if the model is to have general applicability then a similar relationship between evapotranspiration and pasture growth should exist for all sites that have the same value of *k*.

This however, is not easy to validate, as it is difficult to assess independently whether two sites that have contrasting microclimates do indeed have similar *k* values. The approach taken in this study was to attempt to make sites on a range of contrasting slopes and aspects uniformly non-limiting in terms of nutrient supply. If this was indeed achieved, then all sites should have a uniform (and high) value of *k*.

The calculated *k* values for the plus-N plots have already been presented in Table 7.2. Clearly they are not all equal. Values of *k* range from 23.8 to 36.6 – a range of 54 %. However, when it is considered that the range in annual pasture production on these "plus-N sites" was from 8271 kg D.M./ha to 18629 kg D.M./ha – a range of 125 %, then it appears that the evapotranspiration model has been effective in accounting for over half of this variation.

There are at least three possible reasons why the values of *k* on the plus-N plots are not as uniform as expected. These are:

- the assumption that pasture growth rate is proportional to evapotranspiration is false.
- the assumption that pasture growth rate is proportional to evapotranspiration is true but there are errors in the model's estimate of evapotranspiration.
- despite addition of non-limiting N, there are ongoing differences in nutrient supply between sites.

Evidence has already been presented to support the second of these possibilities, and later in the Chapter, consideration is given to modifying the model to improve its prediction of evapotranspiration.

However, as a first approach to modeling, the key assumptions of the model were assumed to hold true and a single average value for *k* (28.5) was calculated from the values for all the plus-N plots in Table 7.2. This value was then used to calculate pasture growth using Equation 7.1.

Figure 7.16 shows that when a single *k* value (28.5) is used, the model can account for much of the variation in pasture growth caused by varying microclimates (assuming unlimiting nutrient conditions have been achieved).

The data point which fits the pattern least well is the HPNE site. It produced the highest total growth by a considerable margin, whereas the model predicts that the flat sites should produce the highest total dry matter. This data point drags the top of the regression line down and lowers the slope. Theoretically, if modeled and measured values agreed perfectly, the slope should be 1.00 and the intercept should cross at zero. However the slope is 0.70 and the regression line intercepts the y axis at 3800 kg D.M./ha/yr. If the NE sites are removed from the regression, the fitted line is $y = 1.04x + 59$, with an R^2 of 0.78 (regression not shown). This is a very good fit indeed. The reasons for the poor prediction of production on the NE sites are discussed later.

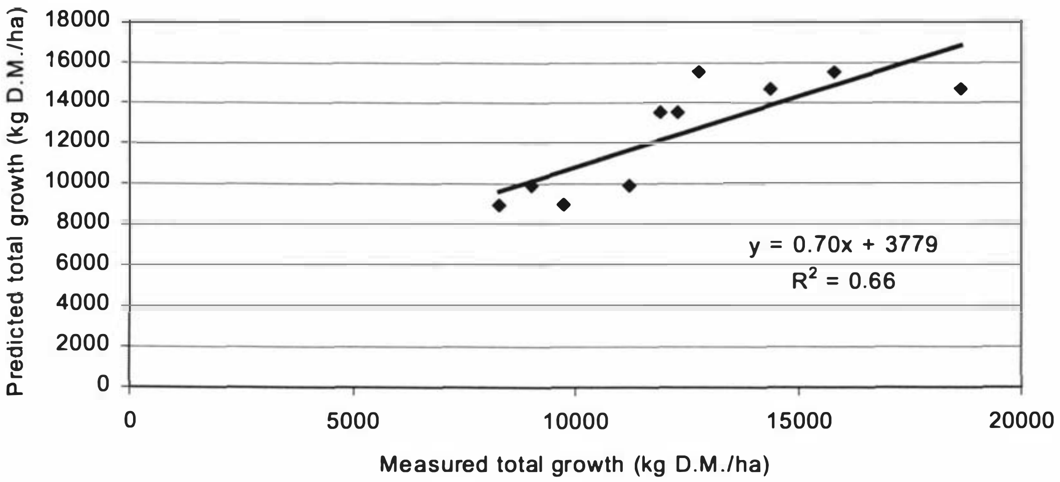


Figure 7.16 Comparison of measured total growth and predicted total growth when *k* is calculated by averaging both LP and HP treatments.

To test the ability of the pasture growth model (equation 7.1) to predict seasonal production, the measured average daily growth rates on a cut-by-cut basis were compared with the predicted growth rates using the single average value of *k* (28.5) on all sites (Figure 7.17).

The R^2 of 0.44 is less than that observed in Figure 7.11 ($R^2 = 0.49$) when individual *k* values for each site were used. This is to be expected as the constant *k* value across all sites has introduced more variability, by not accounting for the measured differences in total annual pasture production , even after evapotranspiration has been accounted for.

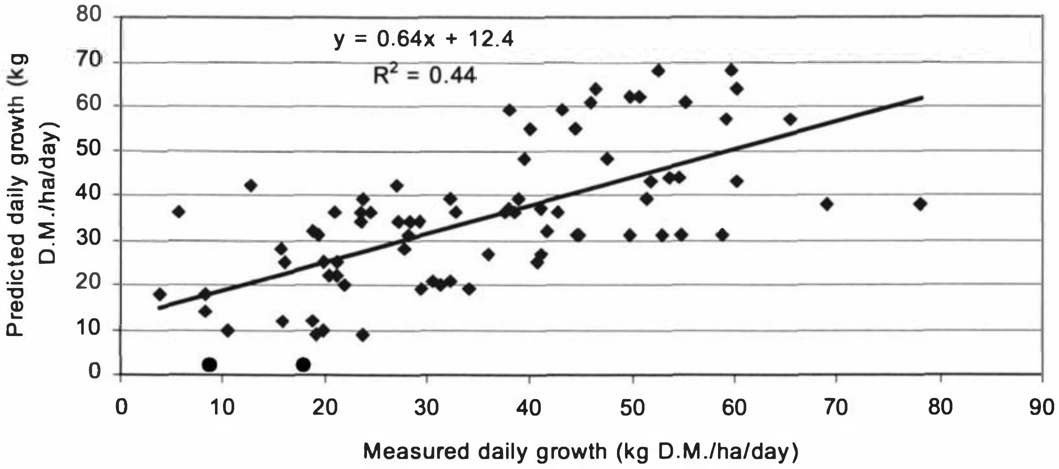


Figure 7.17 Relationship between measured and predicted daily growth rates for unlimiting-N sites, averaged for the 8 growth periods when a single *k* value of 28.5 is used.

Although the data in Figure 7.17 give an overall indication of the ability of the model to predict pasture growth rates on a cut-by-cut basis, this does not allow more detailed analysis of those seasons and sites where the model is behaving particularly poorly – or conversely - particularly well.

To provide this more detailed analysis, the measured cumulative pasture production on the LP and HP sites receiving non-limiting N was compared with the modeled values for each site (Figures 7.18, 7.19, 7.20, 7.21 & 7.22).

Overall, as indicated in Figure 7.17, the model does a reasonable job of accounting for the wide variations in the rate of pasture production, both between slopes and aspects, and also over time. However, the agreement between modeled and measured data is better on some sites than others. Inspection of Figures 7.18-22 enables a number of general observations to be made. Some of these were also noted when considering the outlying data in Figure 7.11 in the previous section.

1.) Figure 7.18 shows the comparison of the predicted and measured cumulative growth for the NE sites. The model agrees very well with the LP sites throughout the year. However, the HP sites produced much more pasture than the model predicts from the start of spring through to the end of February. This pattern of significantly increased growth in summer on the HP plots relative to the LP plots was also observed on most other sites (Table 6.8). Moir *et al.* (2000) also found that pasture growth on LP and HP sites diverged markedly when soil moisture became limiting on sites with low to medium rainfall

Although this is clearly a "fertility" effect, the cause of the extra pasture growth may be more complex than just the P deficiency being overcome. Smika *et al.*, (1965) found that pasture used more water as long-term fertiliser application increased. This observation was explained by postulating a greater pasture rooting depth, which increased the available water during dry periods.

In this trial, the increased availability of P on the HP treatment may have enabled the pasture to form a deeper rooting structure and thereby provide the pasture with extra water for growth during dry periods (from spring onwards). For example, if the assumed depth of available water in the model was increased from 75 mm to 150 mm, the predicted growth on NE sites would increase from 14495 kg D.M./ha/yr to 17648 kg D.M./ha/yr.

Therefore, whilst some of the added pasture response on the HP sites might be attributed to faster growth due to a P deficiency being overcome, a great deal of the response may in fact be due to "extra days" of pasture growth during dry periods.

2.) The model generally over-predicts pasture growth on southerly and flat sites in mid to late summer. As noted earlier, this may possibly be caused by hydrophobicity causing a variable proportion of summer rainfall to be lost in surface runoff, rather than infiltrating into the soil and being available for plant uptake.

3.) The model under-predicts pasture production on most sites from early to mid spring. Over the same period, the model also under-predicts soil gravimetric water content (section 7.4.1). Thus, it seems that the model predicts that the soil dries out more quickly than actually occurs - resulting in less water for plant uptake. A possible explanation is that after a wet winter, during which the whole soil profile became fully wetted, capillary movement provided water for plant uptake from below the top 75 mm of soil. The same effect did not occur in the summer dry spell as the soil profile was not fully recharged at that time, and thus there were not the reserves of water deeper in the profile to draw from.

4.) The model under-predicts pasture growth on SS sites from mid autumn through to the end of winter. This under-prediction of growth rates in winter is likely to be due to an over-simplification in the radiation calculations. The model calculates that the SS sites receive very little radiation in this period, and thus predicts a very low evapotranspiration rate. This is likely to be correct. However, convection currents possibly bring warm air from the northerly facing slopes onto the SS sites, thus causing higher rates of evapotranspiration than the model predicts.

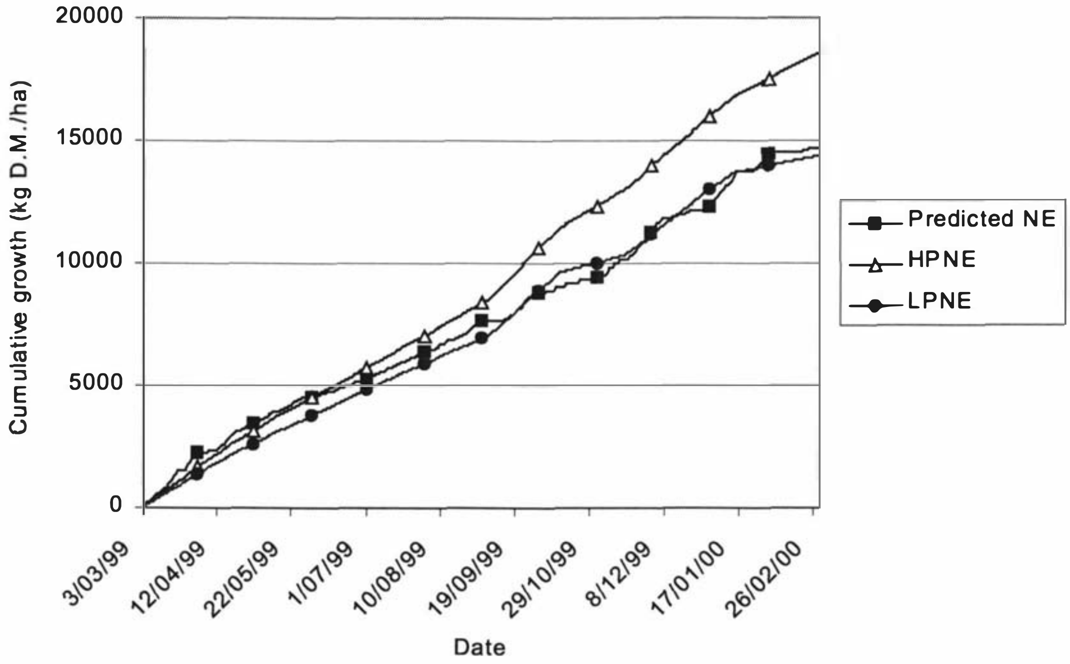


Figure 7.18 Measured and predicted cumulative pasture growth on NE sites receiving non-limiting N.

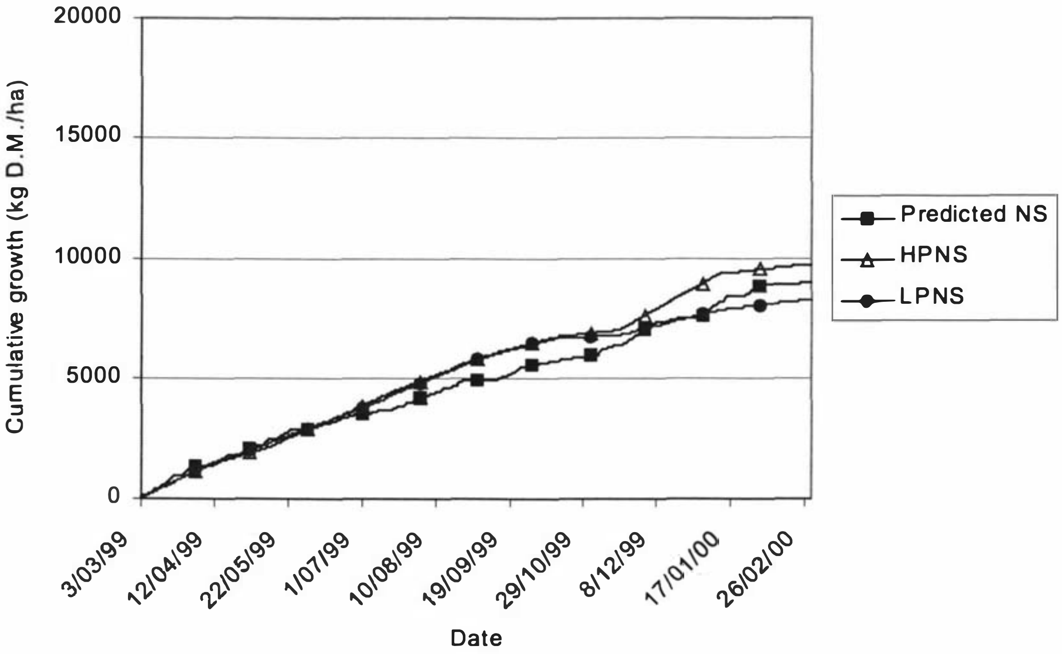


Figure 7.19 Measured and predicted cumulative pasture growth on NS sites receiving non-limiting N.

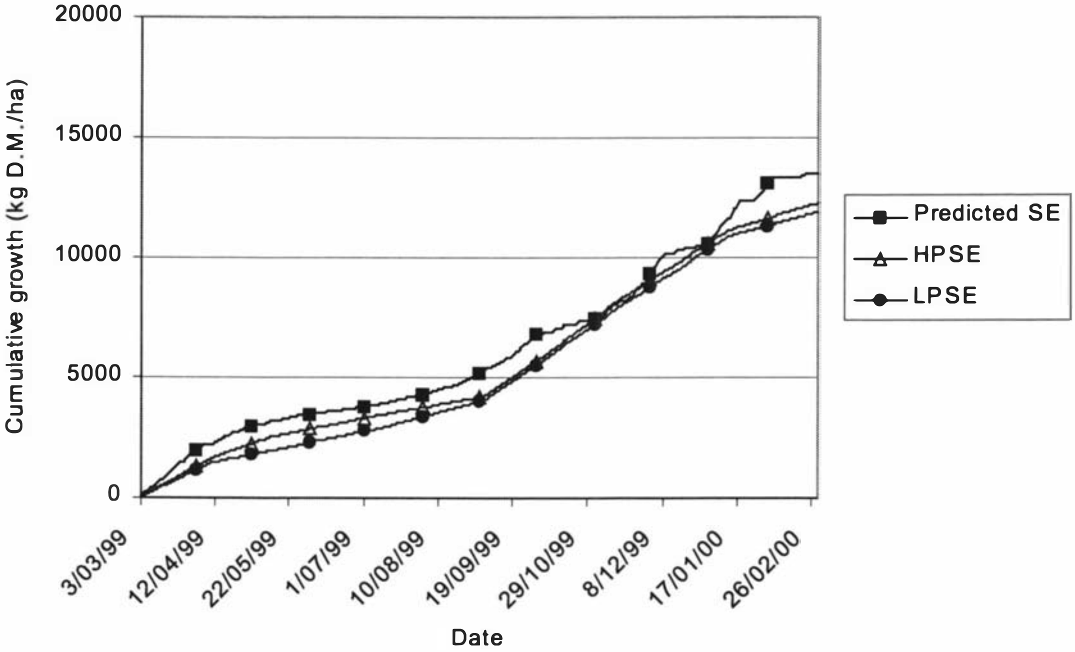


Figure 7.20 Measured and predicted cumulative pasture growth on SE sites receiving non-limiting N.

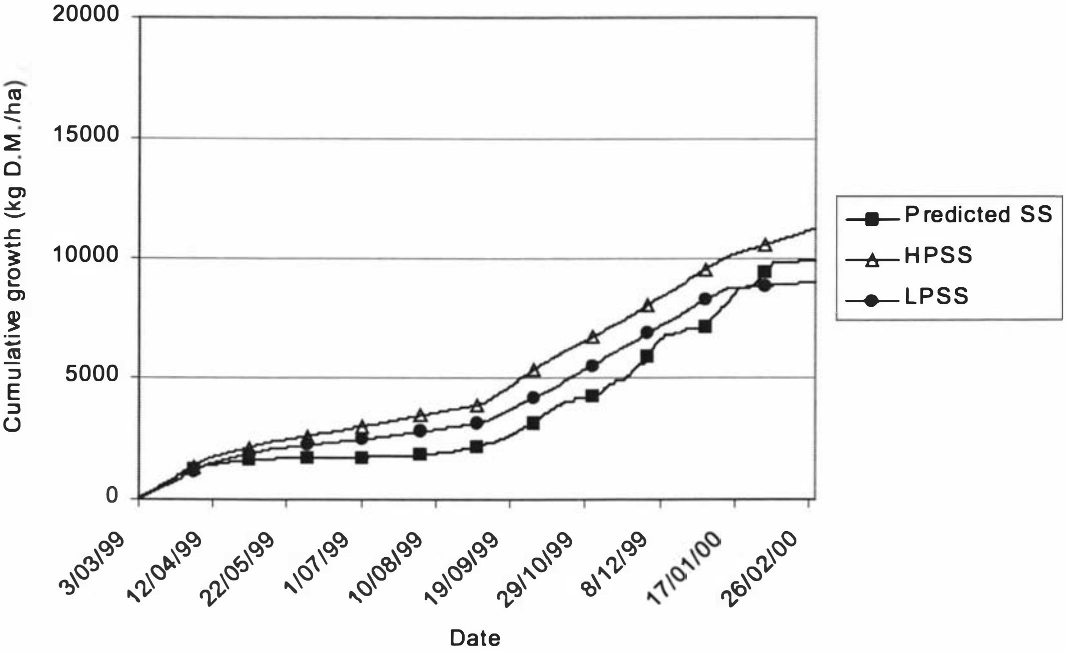


Figure 7.21 Measured and predicted cumulative pasture growth on SS sites receiving non-limiting N.

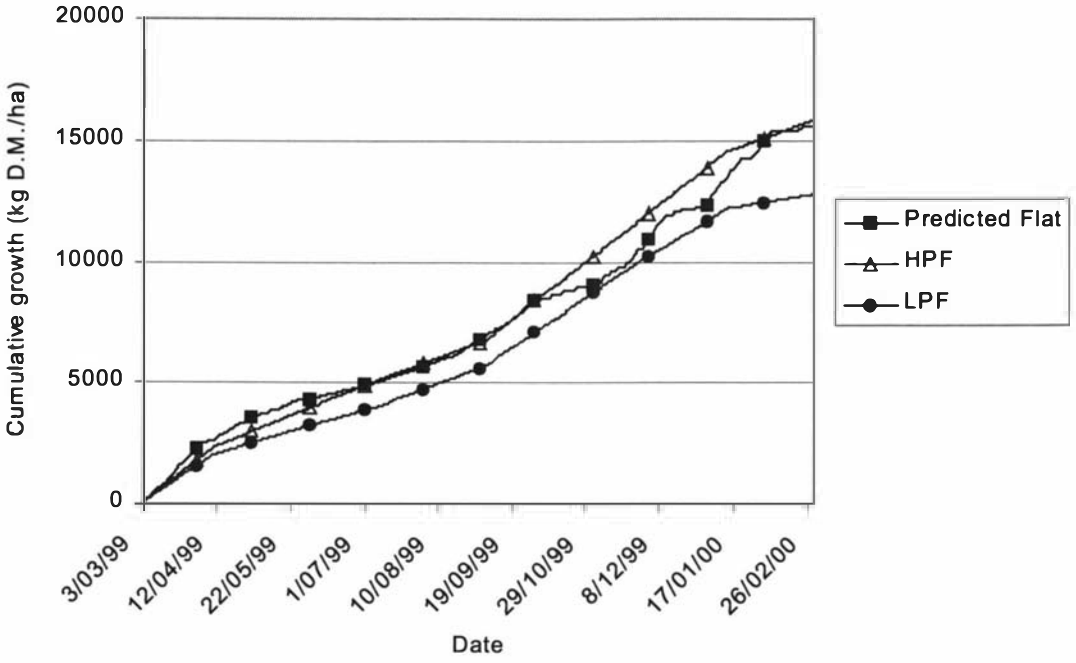


Figure 7.22 Measured and predicted cumulative pasture growth on flat sites receiving non-limiting N.

Overall therefore, the model appears to predict pasture growth very well on a range of varying aspects and slopes, which provide some vast differences in microclimate, using a single growth factor (*k*) for both LP and HP treatments.

In this first approach to modeling it was assumed that by making N non-limiting, all nutrient restraints on pasture growth would have been removed. Certainly, the data presented in Chapter 6 indicate that N availability has a much greater impact on pasture growth at this site than P availability.

However, there was a small, but significant, effect of P status on pasture growth within the trial, and therefore even in the presence of non-limiting N, pasture on the LP sites would be restricted in growth. In terms of the model this would be reflected in a reduced *k* value and as a result the data in Table 7.2 do have slightly lower *k* values for the LP plus-N plots. Figures 7.23 and 7.24 show the comparisons between measured and predicted annual pasture production when the individual *k* values for HP and LP sites are estimated separately (Table 7.2). There are much better relationships between measured and predicted annual pasture yields, when separate *k* values are used for HP and LP sites, than when a single *k* value averaged across all the plus-N plots is used (Figure 7.16).

The pasture growth prediction for the LP data is better than the HP data, with R^2 values of 0.89 and 0.73 respectively. Once again, the higher than predicted production on the HPNE sites reduces the slope, increases the intercept and decreases the R^2 value of the fitted line for the HP plots.

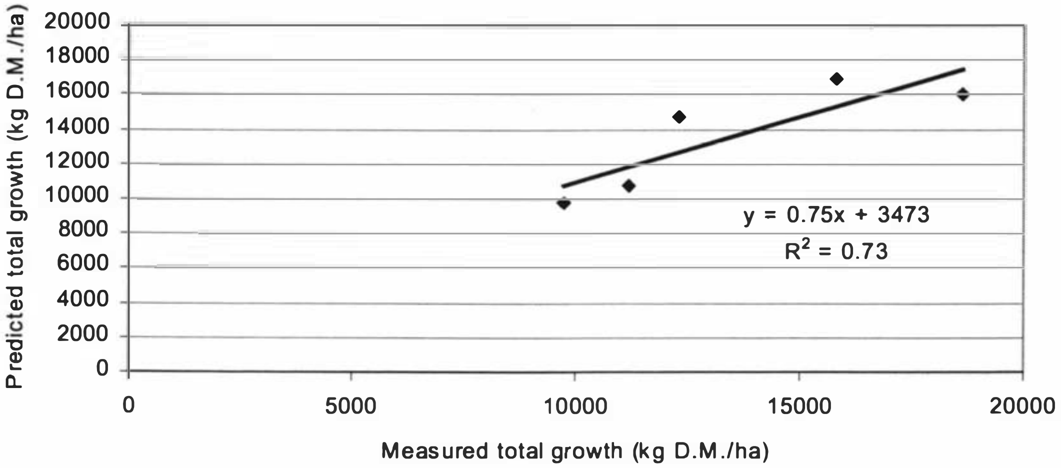


Figure 7.23 Comparison of measured total growth and predicted total growth when *k* is calculated by averaging HP treatments.

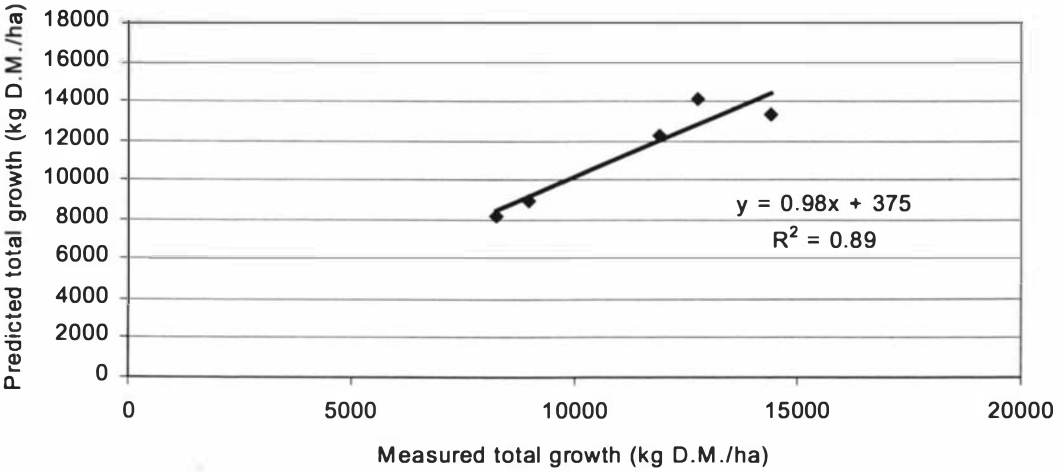


Figure 7.24 Comparison of measured total growth and predicted total growth when *k* is calculated by averaging LP treatments.

7.5 MODEL OVERVIEW

The model consists of two principal components. The first is a climate sub-model that predicts evapotranspiration from readily available input parameters. The second component is the main model that calculates pasture growth rate from evapotranspiration assuming a constant (k) related to soil fertility.

The climate sub-model appears to work well, and is able to predict with reasonable accuracy the fluctuations in gravimetric soil moisture throughout the year. Day-to-day fluctuations are harder to predict and validate, due to the short duration of some high intensity rainfall events.

In general, the main model (using a single value of k) predicts with a fair degree of accuracy the total annual pasture growth on the HP treatments that had received non-limiting N. Detailed inspection of the discrepancies between predicted and observed pasture growth rates reveals that a large percentage of the scatter from the fitted line comes from four key areas. These are:

- An overall under-prediction of pasture growth rates on NE sites
- An under-prediction of pasture growth rates on SS sites in winter
- An under-prediction of pasture growth rates on all sites except for NS, in early to mid spring
- An over-prediction of pasture growth rates on SE, SS and flat sites in mid to late summer.

These issues will be considered briefly in turn.

The NE sites perhaps need to be viewed differently to the other sites. As was mentioned in previous chapters, NE sites (even in the absence of added N) have better conditions for pasture growth throughout the year due to warmer temperatures than southerly aspects and fewer water restrictions than steep slopes. These favourable conditions promote more vigorous pasture growth than on the other sites investigated in this trial, and in turn increase the rooting depth of pasture on the NE sites. The effect of this is to increase the amount of water available for plant growth.

As mentioned earlier, the model in its simplest form assumes a constant rooting depth of 75 mm across all sites. Therefore if the model is going to be used in the future for fertiliser recommendations, an adjustment may need to be made for NE (and perhaps other) sites. The most practical and justifiable adjustment is to change the rooting depth, which in turn changes W_a. The approach may be as simple as making a visual assessment of rooting depth on different aspects and slopes by digging a few holes and examining soil profiles. Allowance for different rooting depths is easily made within the model structure. Woodward et al. (2001) used a rooting depth factor when modeling soil water deficits in New Zealand pastures.

The development of a greater rooting depth (and increased growth in dry periods) as a result of increased fertility, raises an interesting point in relation to N fertiliser use. In general, most farmers view the application of N fertiliser as a form of "buying" supplementary feed. This is largely due to the fact that N is lost from the soil-plant system relatively easily and does not build the long-term fertility of the soil (as P is thought to do). However, this study has shown that pasture growth can be increased significantly by N fertiliser application, which if it is applied long term is likely to also increase the pasture rooting depth significantly. Therefore, the application of N fertiliser may provide a means by which to strengthen pasture against drought (a major limitation to pasture growth on the east coast).

The model significantly under-predicts pasture growth on SS slopes during winter. In the previous section this was attributed to convection currents bringing warmer air from north-facing slopes and thus providing warmer temperatures than would be calculated by incident radiation alone. A simple modification to the model to overcome this under-prediction on SS sites during winter may be to assume a minimum E_t rate when moisture is unlimiting. Calculation of the E_t rates from the measured SS sites during the winter shows that an average of 0.40 mm of E_t occurs each day. Recalculation of the model using these data (Fig 7.25) improves the fit between measured and predicted cumulative pasture production compared to that obtained with the original model (Fig 7.21).

The over prediction of pasture growth during mid to late summer is however, more difficult to remedy, as is the general under-prediction of pasture growth in spring. As was discussed in the previous section, these difficulties are thought to result from errors in the estimation of available water in the soil.

In spring, the model under-estimates the available water – possibly because of recharge from soil at greater depths that has been wet up during winter. In summer, the opposite is the case, with the model over-estimating the amount of available water – possibly as a result of hydrophobicity preventing infiltration of summer rainfall and causing surface runoff. However, in neither of these situations, is there sufficient quantitative information available, to justify an adjustment to be made to the model.

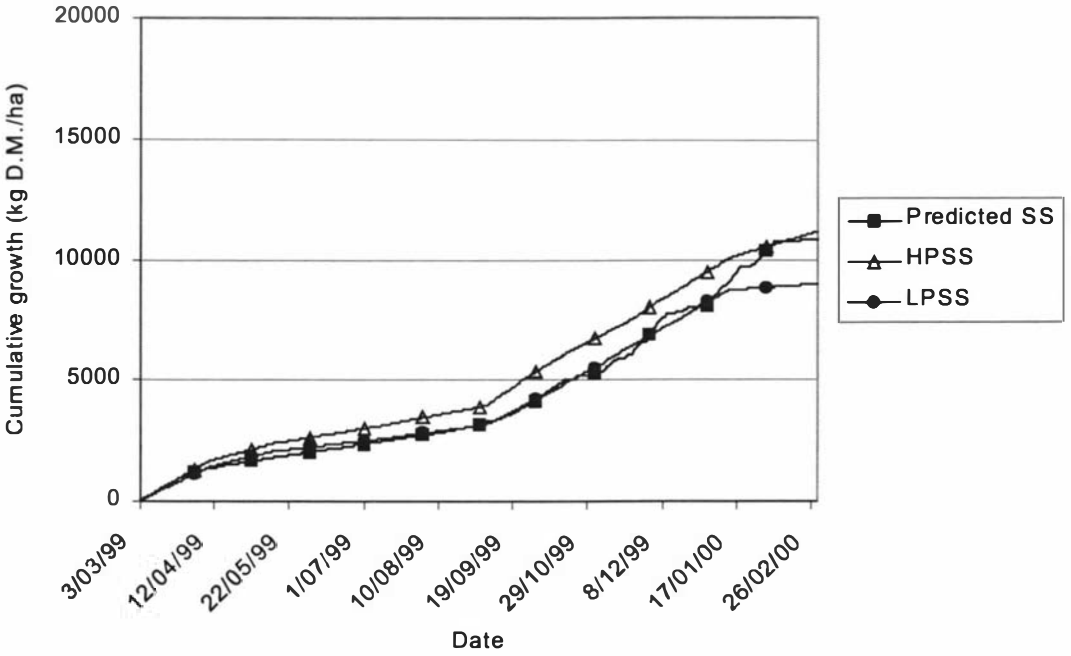


Figure 7.25 Measured and predicted cumulative growths for SS sites using the readjusted model.

To examine the effect of the possible improvements to the model outlined above, predicted pasture growth rates were calculated for each of the 8 growth periods on the HP plots that had received non-limiting N, using the original model, including the *k* value of 28.5 that had been obtained by averaging the *k* values for all the plus-N plots (Table 7.2). These predicted pasture growth rates were plotted against measured values in Figure 7.26.

The model was then modified by:

- Correcting the evapotranspiration rate on SS sites in winter to a minimum rate of 0.4 mm/day.
- Adjusting the depth of available water on NE sites to 150 mm. This altered the total amount of evapotranspiration and subsequently the value of *k* on NE sites.
- Recalculating the average *k* value, using only the HP plus-N sites (Table 7.2) and including the new value of *k* (30.2) calculated for the HPNE site. The new value of *k* used in the model was 29.8.

The recalculated predicted daily growth rates provide a slightly better fit ($R^2 = 0.52$) with the measured daily growth rates on HP sites (Figure 7.27) than the basic model. The under-prediction on all sites, except NS, in early to mid spring still creates a lot of scatter along with the over-prediction of pasture growth rates in mid to late summer on SE, SS and flat sites.

However, when the recalculated *k* value (for HP sites) is used to calculate annual pasture production, there is a much improved relationship between predicted and measured values on HP sites ($R^2 = 0.94$ as opposed to 0.73) (Figure 7.28).

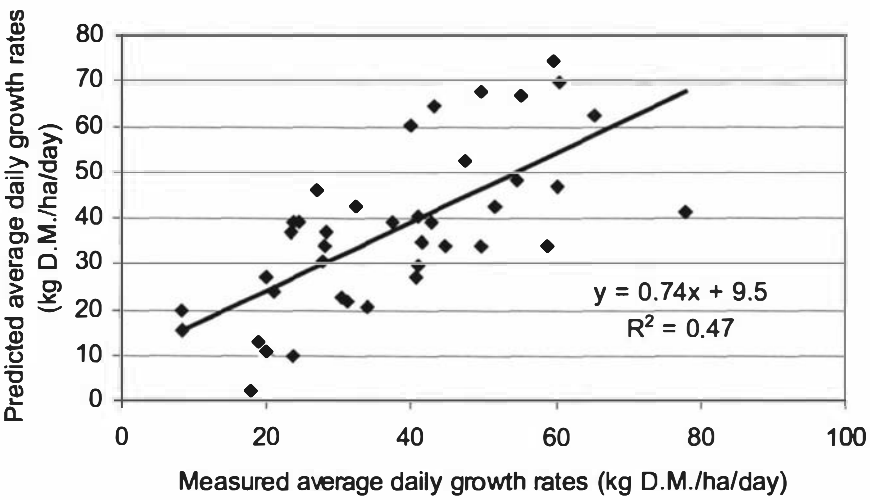


Figure 7.26 Relationship between measured and predicted daily growth rates for HP non-limiting N sites, averaged for the 8 growth periods when a single *k* value of 28.5 is used.

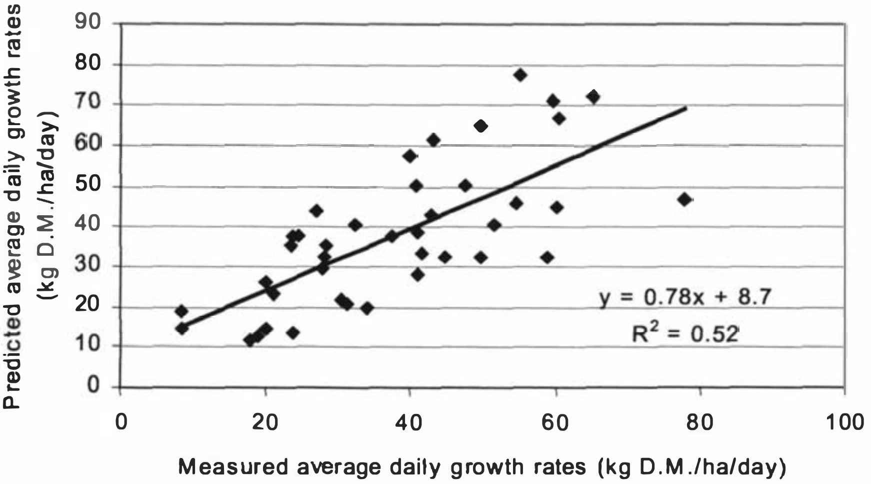


Figure 7.27 Relationship between measured and predicted daily growth rates for HP non-limiting N sites, averaged for the 8 growth periods when amendments have been made to the depth of available water on NE sites and winter growth rates on SS sites.

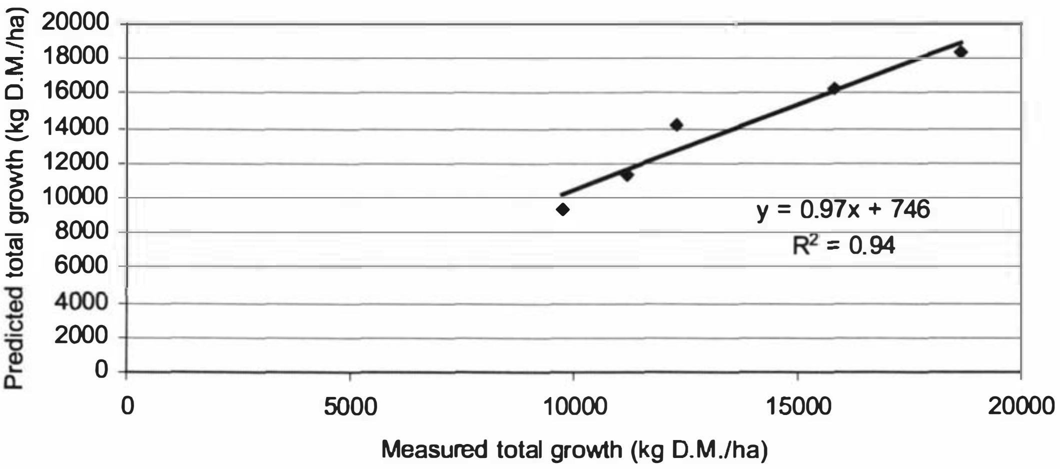


Figure 7.28 Comparison of measured total growth and predicted total growth on HP sites when suggested adjustments have been made using an adjusted *k* value for HP sites only.

7.6 RELATIONSHIP BETWEEN *k* AND FERTILITY

If the assumptions in the model are correct, then the value of *k* is an estimate of the integrated constraints placed on pasture production by soil fertility. The greater the constraint from soil fertility, the lower the pasture production and therefore the lower the value of *k*.

This was demonstrated in the previous section by the lower values of *k* for the LP plots relative to the HP plots.

Values of *k* were therefore calculated for each of the sites in the absence of any added N fertiliser (Table 7.3). As expected, these values of *k* are lower than the *k* values calculated for the corresponding sites in the presence of non-limiting soil N. Also, once again, the small P response observed at the site results in a slightly lower average value of *k* on the low P sites.

Table 7.3 Table showing the total growth of LP and HP site (N-limited), the calculated total E_t and calculated *k* values (once suggested alterations to the model have been made).

Treatment	Total growth (kg D.M./ha)		Total evap (mm)	Calculated *k*	
	LP	HP		LP	HP
NE	6178	9099	617	10.0	14.7
NS	2454	2415	314	7.8	7.7
SE	4602	5223	474	9.7	11.0
SS	2466	3810	381	6.5	10.0
Flat	5601	6614	545	10.3	12.1
Mean	**4260**	**5432**	**466**	**8.9**	**11.1**

Assuming that *k* represents soil fertility constraints on pasture growth it might be expected to bear some relationship to conventional soil test values, which are also designed to measure soil fertility.

Regression of *k* against Olsen P revealed absolutely no relationship ($R^2 = 0.006$, regression not shown), despite the fact that the HP sites did produce on average significantly higher pasture yields throughout the year.

This is a graphic example of the difficulties in using Olsen P tests as a surrogate indicator of soil fertility on the range of pasture types in this trial - many of which are primarily N limited rather than P limited.

Mineralisable N should, in theory, be better related to *k* values. Mineralisable N was measured for each replicate plot at each cut. These values were combined to give an average mineralisable N value for each replicate plot for the year.

The relationship between these average values of mineralisable N and the *k* value for the site is presented in Figure 7.29. The relationship is better than for Olsen P – but still far from convincing.

An attempt was made to use a step wise multiple regression to improve the relationship between *k* and soil test measurements. However, when Olsen P was added to the regression of *k* against mineralisable N the fit was not improved at all.

In Chapter 6, it was noted that there were systematic differences between slopes and aspects in the relationship between mineralisable N and pasture production. For a given value of mineralisable N, pasture production was higher on northerly aspects than on southerly aspects. This was explained by the observation that mineralisable N is measured under standard conditions in the laboratory – all samples are treated the same. In the field however, environmental conditions for mineralisation are much better at some sites than others and thus samples that behave similarly in the laboratory may not always do so in situ.

Recognising this, and that mineralisation is strongly influenced by temperature, average annual temperatures were included in the multiple regression of *k* against mineralisable N. The fit improved slightly ($R^2 = 0.25$, regression not shown) but the improvement was not statistically significant.

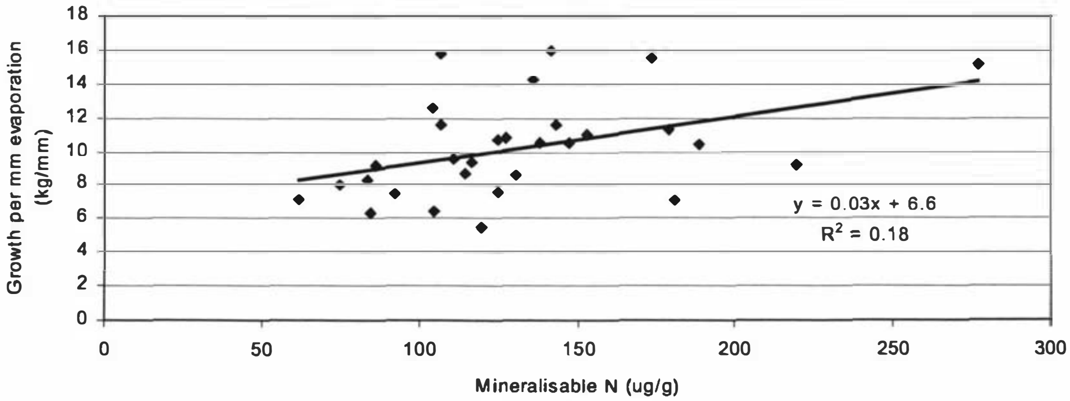


Figure 7.29 Relationship between mineralisable N and calculated *k* values for N limited treatments.

A difficulty with regressions of this type is that considerable error may be associated with the estimation of the *k* value itself. This has been discussed in detail earlier in the chapter. In particular, errors may arise at some sites because of difficulties in estimating E_t.

To explore the implications of this further, four sites were chosen that, in terms of seasonal and annual pasture production, appeared to fit the pasture production model best. These sites were LPNE, HPNS, HPSE and HPSS.

If the global assumptions of the model described in Section 7.2 are true, the close correspondence of these four sites to the model predictions suggests that these values of *k* may be reasonably free of error.

Each of these sites had three replicate plots, giving a total of 12 data points. Plotting these 12 values of *k* against corresponding values of mineralisable N once again gave only a moderate relationship (regression not shown). However, when the data were separated into north-facing and south-facing slopes, reasonably close relationships were observed (Figures 7.30 & 7.31).

Of particular interest is the difference in the gradients of the regression lines. The gradient of the regression line for north-facing slopes (0.09) is over twice that of the south-facing (0.04) slopes.

Once again, this highlights the point that for a given value of mineralisable N measured in the laboratory, soils on warmer north-facing slopes will release more plant-available N than the equivalent soil on colder south-facing slopes.

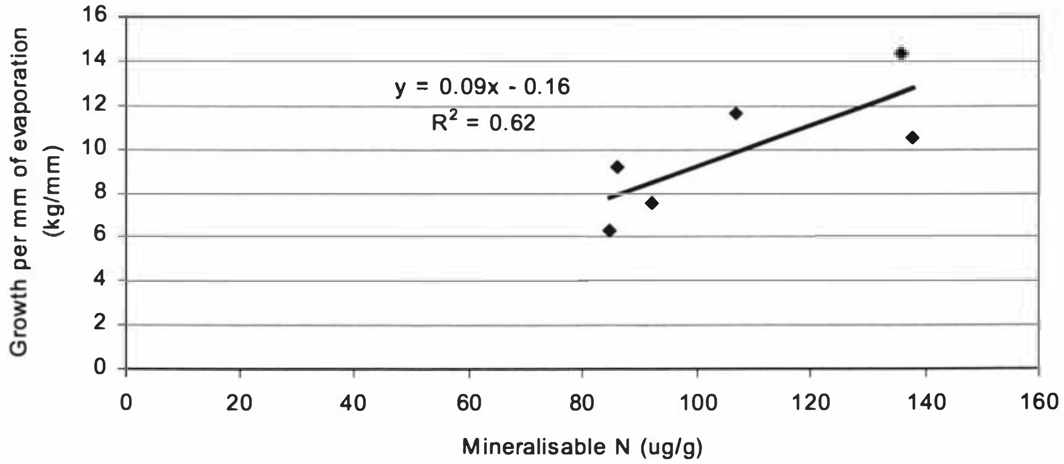


Figure 7.30 Relationship between the calculated *k* values of N limited LPNE and HPNS treatments and mineralisable N.

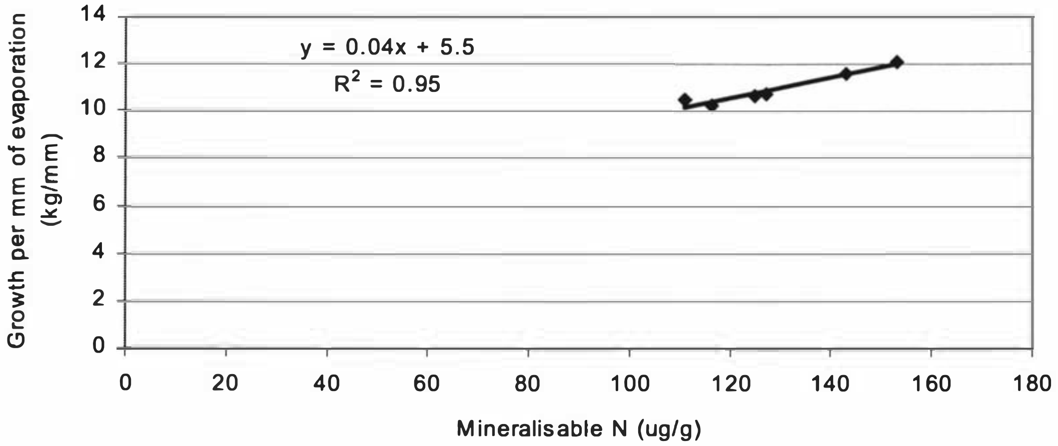


Figure 7.31 Relationship between the calculated *k* values of N limited HPSE and HPSS treatments and mineralisable N.

7.7 MODEL APPLICATION

The model approach proposed originally by Faulalo (1997) and Moir *et al.* (2000), and evaluated in the preceding section, appears to show promise as a way of quantitatively describing pasture growth as it is affected by climate and soil fertility status.

In its final form (Figure 7.28) with a single value of *k*, the model was able to account for the almost two-fold range in pasture production between slopes and aspects with unlimiting nutrient supply with an R^2 value of 0.94.

Not too much can be read into this extremely close fit between observed and predicted pasture production, because the model was adjusted (albeit with reasonable physical justification) to overcome some of the most obvious shortcomings in the original assumptions. A much more demanding test would be to check the predictions of the model against an independent data set at another site. Unfortunately it would require another similar trial using unlimited nutrient supply to provide a uniform *k* value to give an equivalent data set.

Nevertheless, it does seem that on an annual basis the central tenet of the model, namely that pasture production is proportional to evapotranspiration may be sufficiently true to warrant further investigation as a basis for developing pasture growth models in the future.

The model was also able to largely account for the seasonal variations in pasture growth rate that occurred on these contrasting landscape units. This was evident in plots of predicted and measured cumulative production (Figures 7.18 – 7.22).

The regression of predicted against measured pasture growth rates (Figure 7.17) reveals a clear linear relationship, although the R^2 value of 0.44 is not high. This is understandable, because even if the central assumptions of the model hold true absolutely, pasture growth was measured on small areas that have highly variable micro-relief. The replication built into the main trial was sufficient to demonstrate fertiliser effects between treatments. But inevitably in hill country grazed pastures, there will be considerable variation within landscape units designated on the basis of general slopes or aspects.

Even without a knowledge of the exact k values that are applicable to an area, the model still has the potential to provide farmers with useful information. Technology such as Geographical Information Systems (GIS) and Remote Sensing will increasingly enable a farmer to determine what percentages of their property fall into each category of aspect and slope. When this information is combined with knowledge of average weather patterns, or a long term forecast, predictions of potential pasture growth rates can be made using the model. The model can be expanded to calculate for any number of aspects and slope categories, depending on the topography of the farm.

Predictions of potential pasture growth rates can be a valuable tool for managing stocking rates and farming policy. Knowledge of where the most pasture is grown and at what time of the year, can help a farmer decide on fence placements, grazing rotations, and timing of fertiliser application. Previous weather data can predict how often a good production year or a bad production year may occur and likely pasture productions in those years. Such information is valuable for long term budgeting.

As an example of applying the model to previous weather data, twenty years of predicted E_t rates were calculated for the Waipawa trial using data from 1972-92 (Table 7.4). The values shown are only yearly totals, however the model can be used to calculate seasonal totals if desired. When the total E_t rates for the trial period (Table 7.2) are compared with the 20 year data, it can be seen that the trial year was approximately an average year. In a good year potential production is approximately 20 % greater, whilst in a bad year potential production is approximately 20 % less.

Points of note from the 20 years of data are the similarity in the mean total evapotranspiration values between the flat and NE treatments and the NS and SS treatments. In reality, the NE values are likely to be higher due to reasons discussed above which have not been taken into account in this model. There is also a much greater variance between maximum and minimum values in the SS treatment than in the NS treatment even though they have a similar mean.

As was discussed in Section 7.3, not all of the climate parameters required for operation of the model will be available on individual farms. However, inputs such as radiation and sunshine hours are not likely to vary all that much between districts within a region and can therefore be sourced from the nearest meteorological station. Temperature is likely to vary between regions, particularly with altitude. However, this can be easily corrected with a simple adjustment (Moir *et al.*, 2000). Rainfall though, is particularly variable between area's, and so the model will require rainfall information from the site in question, in order for it to be sufficiently accurate to provide useful information. A large percentage of farmers collect rainfall data on their properties, however the regularity of collection will not always be on a daily basis. In order to test the robustness of the model for less frequent rainfall collection, rainfall over the trial period was summed into five day intervals.

Using rainfall data collected only every five days did not significantly alter the evapotranspiration rates calculated by the model, therefore showing that the model could easily be transferred to a new area or region with less frequent rainfall data collection.

Table 7.4 Total calculated cumulative E_t (mm) from each treatment for the years 1972-1992.

	Flat	NE	NS	SE	SS
Maximum	614	606	397	545	423
Minimum	418	422	291	371	269
Mean	516	503	339	461	356

7.8 CONCLUSIONS

Moir *et al.* (2000) showed that pasture growth was strongly related to evapotranspiration. The model developed in this study showed that E_t can be calculated on varying aspects and slopes, and can be related to pasture growth. The model in its simplest form however, is inaccurate on some sites at some stages of the year. With some adjustments the model can be made more accurate. What is not known though, is whether the adjustments, such as pasture density, rooting depth, and minimum evapotranspiration rates can apply to other regions? Other factors which the model does not take into account, are intensity of rainfall, whether or not more runoff occurs on steeper slopes, what effect hydrophobicity has on the soil's ability to rewet, and soil water recharge from below the soil surface (capillary action). All of these factors will have an effect on the soil water balance and therefore on the model's predicted E_t rates.

In this study, westerly and easterly aspects were not studied. While it is possible for the model to easily be applied to other aspects it is impossible to say whether predicted E_t rates will agree with measured rates, as adjustments may be required on those sites as well.

The measured pasture growth data tended to indicate that increased long term soil fertility increased rooting depth which increased pasture growth in dry periods. Therefore, application of fertiliser not only increases pasture production by removing nutrient constraints, but also by increasing the growth period of the pasture. Increasing the soil's fertility can be viewed as a method of strengthening pasture against drought.

Soil mineralisable N and Olsen P were poorly related to *k* when all sites were considered together. However, mineralisable N was better related to *k* when sites were separated into north and south aspects. This variation in the relationship between mineralisable N and *k* on the north and south aspects, will pose problems if mineralisable N is going to be used for predicting pasture growth in conjunction with the model. It would require that a different index be developed for each aspect, including east and west. Therefore, temperature which has a major effect on mineralisation processes (Kai *et al.*, 1969; Campbell and Biederbeck, 1972; Stanford *et al.*, 1973; Ross and Bridger, 1977; Carran, 1979; Ledgard *et al.*, 1989; Clough *et al.*, 1998) may need to be included in some way in the calculation of *k*.

The reasonably close agreement between predicted and measured growth rates by the model shows that there is potential for using a modified approach from that developed by Moir *et al.* (2000) on country with varying topography and microclimates. The model also showed that there is the potential for using climatic data to aid interpretation of results in agronomic field trials, however further work is required to test some of the model inputs for other hill country locations and in wetter climates.

CHAPTER 8

SUMMARY AND CONCLUSIONS

In this study, the trial site provided a location which had a wide range of varying soil properties and microclimates “typical” of dryland hill country. It therefore, provided an ideal situation to examine some of the major factors affecting and limiting pasture growth on this type of country.

A major point which comes out of the study is that the dryland hill country production system is extremely variable, both temporally and spatially due to a number of factors. These factors range from microclimate to the animal transfer of nutrients. The combination of these factors, means that pasture growth varies enormously within sites, as well as between, sites throughout the year. This study has attempted to isolate and identify the individual factors which have caused these variations and subsequently determine the extent to which each factor limits growth.

Above all else, the major factor which appears to control and limit pasture growth is the supply of N. Pasture growth rates measured in the presence of unlimited N ranged from 3.8 – 78.0 kg D.M./ha/day. Growth rates measured in the absence of added N fertiliser ranged from 1.1 – 34.5 kg D.M./ha/day. The response (or level of restriction from maximum potential growth) ranged from 2.7 – 45.4 kg D.M./ha/day indicating that the level of response (or degree of depression) was greater than that being currently produced on that country.

Whilst, the pasture growth rates and levels of N response varied largely between sites and growth periods throughout the year, the total annual N response did not vary greatly.

In terms of total annual pasture production in the presence of non-limiting N, the NE sites produced the most pasture, followed by the flat sites, with the SE and SS sites producing similar amounts and the NS sites producing the least. The seasonal pasture growth rates throughout the year however did not follow this pattern as each site became limited by different factors at different times. Energy inputs, consisting largely of solar radiation, appeared to cause a great deal of the variations. The reason energy inputs vary between aspects and slopes is because of the sun's pattern of movement across the sky. In the southern hemisphere, the sun rises in the east and follows a northerly direction before setting in the west. In summer the sun's path is much higher in the sky, than in winter when it is lower in the sky. This leads to northerly aspects receiving a greater amount of direct sunlight, and subsequently higher energy inputs, throughout the year than southerly aspects. The trend is reversed for a short period in summer when the sun rises and sets from a slightly southerly direction. This variation in energy inputs causes differences between the aspects on a number of levels.

The first variable which it has a direct effect on, is pasture growth. Pasture is reliant on sunlight for photosynthesis, and most plant cell reactions are temperature dependant. Therefore, the higher energy inputs on the northerly sites leads to them having a greater potential pasture growth rate. However, the higher energy inputs also means that a higher rate of evaporation occurs, which coupled with a lower moisture holding capacity than on southerly sites means that soils on northerly aspects dry out and become moisture deficient more readily than southerly aspects. Therefore, when rainfall is limiting, the higher energy inputs and greater potential growth on the northerly aspects is balanced out somewhat by the fact that these sites experience greater moisture limitations. Moisture limitations affect the NS slopes more than the NE slopes due to greater stoniness and shallower soil depth.

Another variable which the energy inputs affect is the soil fertility. Soil testing examining the total N and P and mineralisable N values of soils on varying aspects, showed that the southerly sites generally had a higher level of measured fertility than the northerly sites. Animal transfer which generally favours the southerly aspect can account for some of the difference (mostly total P), however, a large proportion of it is due to the differing rates of microbial processes, which are very temperature dependent. The higher energy inputs on the northerly aspect cause the soil temperatures to be higher and consequently processes such as mineralisation are higher on those sites. The lower measured fertility on the northerly sites can therefore be put down to a combination of factors. NS sites, due to moisture restrictions, produce the least amount of pasture, which leads to the lowest amount of return of organic material to the soil. The higher rate of breakdown of organic material due to higher mineralisation rates means that these sites have very little organic matter in the soil and consequently lower amounts of nutrients. NE sites produce more pasture, and will have higher rates of return of organic matter back into the soil. This is also aided by the relatively lower animal transfer losses from easy than steep slopes. However, the higher mineralisation levels on northerly sites means that more of the organic matter is converted into plant available nutrients and taken up by pasture than on southerly sites, where a larger percentage of the returned plant material remains in organic form. Consequently the southerly sites have higher total N and P tests, along with higher mineralisable N values than northerly sites.

The effect of temperature on mineralisation rates is important in relation to the supply of N to pasture and the variations in growth rates between various sites. In the absence of added N fertiliser the primary source of N to pasture is through the mineralisation of organic material into plant available forms of N.

Having a soil test that can determine the availability of N is important. In more moist climates, where adequate clover growth can be achieved, the Olsen P test is used as an indirect index of N availability due to the increased growth of clover with increased P fertility. However, in dry climates where clover growth is limited, the Olsen P test is not applicable. Therefore, a more accurate N availability test is required. The ammonium and nitrate tests were shown to be too variable and so are of no value. The mineralisable N test though, appeared to show some potential for estimation of N availability and the subsequent relationship with pasture growth. However, the effect of temperature on mineralisation rates appeared to decrease the test's applicability to hill country due to the varying energy inputs between aspects.

This was highlighted on the NE sites which had a low mineralisable N test but provided the highest pasture growth rates. Temperature was therefore, assumed to be an important factor altering the relationship, allowing more N to be mineralised than the test indicated. This is likely to occur as a result of the test being carried out at a set temperature (35°C), whereas in the field, soil temperatures vary markedly between sites. Therefore, whilst the mineralisable N test can measure the amount of mineralisable N that is available to be mineralised, it cannot detect what percentage actually gets mineralised. It may be the case that the northerly sites mineralise all of the "available" N, whilst the southerly sites mineralise a much smaller percentage of the measured potential. This means that for the test to be more accurate in hill country, the difference in soil temperature needs to be accounted for.

It was expected that by providing pasture with non-limiting amounts of N, the major soil fertility growth restrictions on pasture would be over-come. This was based on the assumption that much of the measured P responses in most studies was due indirectly to the increased levels of soil N from increased legume growth. However, this study showed that even when unlimiting N conditions were achieved there was a measurable and statistically significant increase in pasture growth due to increased P fertility (except for SE sites). Whilst some of this effect may have been due to some P deficiency being overcome, a large proportion of the difference in growth rates between LP and HP treatments occurred when moisture became limiting. It has been suggested in the past that this effect is due to the uptake of P occurring by diffusion which is reduced when soil moisture becomes low. However, it is argued in this thesis that the difference may be due to a greater rooting depth on the HP treatment which allows more water to be sourced when moisture becomes limiting.

Therefore, pasture growth in dryland hill country is affected by a wide range of factors ranging from climatic limitations to fertility limitations, with the two often interrelated. However, considering the chronic N deficiency of dryland hill country, it can be concluded that the potential for N fertilisers is huge. The northerly sites appear to provide the greatest potential from early autumn through to mid spring, and southerly and flat sites providing the greatest potential in early autumn and from early spring through to early summer. In conjunction with N use, increased P fertility also appeared to provide the potential to produce greater pasture responses. If though, the P responses are due to increased rooting depth and increased moisture supply, the consistent use of N fertiliser may provide the same result without the need for increased P fertilisers?

Taking into account the varying growth rates and N responses by different sites throughout the year, the question must be asked whether it is reasonable to farm hill country as a single unit, as is common practice. While some farmers recognise the variations in potential growth between different aspects and slopes and try to adjust their farming policies accordingly, the majority do not. This can be put down to a number of reasons, ranging from a lack of knowledge of the differences, to the lack of technology to farm them as separate units (i.e. fertiliser spreading technology). Nevertheless, there are some major advantages to be gained if the knowledge is applied wisely. For instance, if paddocks can be broadly split into north and south aspects, grazing rotations can be adjusted accordingly to take advantage of the times of the year when production will be highest on each site. That way grazing can be deferred on sites at the times of the year when production is low and thus help to limit damage caused to the pasture by stock and promote growth. If current research into fertiliser spreading technology proves fruitful, higher rates of fertiliser will be able to be applied to the sites with the greater potential responses for the time of the year.

On the other hand, if farms are going to be farmed as a single unit, the findings in this study also raise some possibilities for changes in farming policy. For instance, the balance of aspects and slopes can greatly influence the production potential of a farm. If a farm consists mainly of northerly-facing aspects with mainly easy slopes, the potential production is likely to be much higher than a mainly southerly-facing farm with easy slopes. Therefore, for optimum pasture utilisation the stocking rates on the northerly facing property should be higher than the southerly facing property. Likewise, the timing of N fertiliser application if only a single application is going to be used should change. The northerly-facing property should receive the fertiliser sometime in early autumn, whereas the southerly-facing property will best utilise the fertiliser if it is applied in the late winter or early spring. With farming practices becoming increasingly intensified and cost efficient, it is essential that the farmer understand the varying potentials in pasture growth between different aspects and slopes so that farming policy can be set to maximise those potentials.

There is a wide range of models available which are used as decision support tools, to predict pasture growth and possible fertiliser responses. Most of the models predict growth and responses in terms of relative growth. Relative growth however, does not allow growth to be predicted quantitatively. As was mentioned above, for accurate farm budgeting and economic analysis, farmers must be able to assess pasture growth and fertiliser responses in a quantitative way. Previous work has shown that there is potential for using evapotranspiration as a way of combining the numerous climatic effects into a single factor, from which to predict pasture growth. This study investigated the potential for adopting this type of approach to predict pasture growth on a range of varying aspects and slopes in dry hill country.

The model, which incorporated the effect of aspect and slope showed good agreement with measured pasture growth under non-limiting nutrient conditions. It therefore, appeared that the various microclimates present were largely accounted for. There were certain circumstances where the predicted values did not agree as well with the measured values, and factors such as varying pasture rooting depth and soil hydrophobicity after dry spells appear to be responsible. However, apart from those minor deviations the model accounted very well for the major climatic variations affecting pasture growth under unlimiting nutrient conditions.

The model developed, appears to present the potential for using a new approach by which to quantitatively predict pasture growth. Current mind sets are focussed around analysing how much extra growth can be produced if a certain amount of fertiliser is applied to a pasture. The model however, accurately predicts the maximum pasture growth, so the best approach may be to use a soil fertility index to predict how much below the maximum yield is being produced under defined conditions. It therefore, requires a slight change in the mind set from viewing extra yield as response, to thinking of current yield as a depression from the maximum. A major benefit of this type of approach is that it allows farmers to judge how far below the potential they are running. More accurate cost analysis will allow economic break even points to be calculated.

As noted above, current soil tests appear to have some flaws in their ability to accurately relate to pasture growth, when the pasture systems are essentially void of clover. The mineralisable N test appeared to provide the greatest potential for being used as an accurate indicator of the potential depression of existing pasture production from maximum pasture production. In situ soil temperature however, appears to be a major confounding factor limiting the accuracy of the test.

Overall, dryland hill country provides an extremely variable pasture production system which is affected by a great number of factors. The greatest factor affecting pasture growth appears to be plant available N, which in dryland hill country is inherently severely deficient. The other major factors are mostly climate-related and vary between sites depending on aspect and slope location. The intensification of farming systems demands that these variations can be accurately accounted for so that more accurate whole farm system models can be used to develop farming policy and economic models. Calculating evapotranspiration and the subsequent depression from maximum yield by soil fertility, appears to be a method by which future models may more accurately aid farmers in analysing the efficiency of their system.

CHAPTER 9

FUTURE RESEARCH

This study has discussed and highlighted a wide range of factors which affect pasture growth in dryland hill country with particular focus on the role of N and climate. Whilst the study answered a lot of the questions which surround the reasons for variations in growth, there are a number of areas in which future research could focus to further clarify some of these issues. Some possible areas of future research are discussed below.

1. In dryland hill country, Olsen P is likely to be a poor indicator of soil fertility where there is a lack of clover growth. For any accurate method of pasture growth prediction and response, there needs to be a relevant measurement of soil fertility. The mineralisable N test showed some potential for use as an indicator of soil N availability, however some discrepancies arose in the test as a result of varying soil temperatures between aspects. There is therefore, a need to explore the potential for building in a temperature correction to the test. Or alternatively developing a more accurate measure of soil N availability which can accurately measure the mineralisation potential of varying soils in situ, under prevailing climatic conditions.

2. The potential for N fertiliser use on dryland hill country has been shown to be high. The information in this study though, has only provided growth rates in the presence of unlimiting N conditions. For accurate economic analysis of N fertiliser potential, differential rate trials need to be carried out to assess break even points up to which substantial responses can be gained. For accurate detailed analysis to be made, residual responses will also need to be measured. In wet environments it is commonly accepted that the largest loss of N from the soil system is via leaching, although most of this comes from stock urine patches. Therefore long term fertiliser response from the application of N is generally not considered, as it is assumed that any N not utilised in the short term will be lost. In dry hill country leaching losses are likely to be low. This may allow N fertiliser applied for instance, in autumn to a northerly face

to still provide a response in spring if all of the N is not utilised by pasture in that time. This may allow the differential seasonal responses of differing aspects and slopes to be accounted for in only one or two dressings, minimising application costs.

3. Current methods of yield prediction and fertiliser response are perhaps slightly limited from the point of view that farmers become focussed on a scenario of "if I apply this amount of fertiliser I will produce this much more pasture." A different approach which uses potential growth and views the current difference between actual and potential yields as a yield depression may allow farmers to assess how much below their production potential they are operating. Whilst, this type of approach is only a different way of viewing the same information, it may allow farmers to break free from current mind sets which limit the scope for potential production levels being reached. Instead of farmers limiting fertiliser inputs to how much surplus cash they have and budgeting stocking rates around the subsequent predicted yields. A yield depression approach may allow financial budgets to be formulated in reverse. Maximum production levels and subsequent profit levels can be calculated from which the required fertiliser inputs and costs can be accounted. If costs are above acceptable levels, inputs can be reduced to levels which make economic sense to the type of production system that the farmer is operating, and these limited resources can be targeted at areas that have the potential to derive the greatest returns. Therefore, future research should focus on developing models from an approach of yield depression from potential maximum values.

4. There needs to be improvement on the predictive power of the climate-driven, soil fertility dependent pasture production model (Chapter7) during dry periods. This appears to be as a result of the model failing to take account of differential rooting depths and soil hydrophobicity. Further work therefore, needs to examine the effect of soil fertility status on plant rooting depth, and how this affects readily-available water holding capacity. Factors affecting and causing hydrophobicity need to examined and how they differ between aspects and slopes. Other work which is likely to benefit the understanding and accuracy of the model is examination of the effect of prolonged

dry spells on plant function and density (especially the effect when the dry spell is broken) and the effect on soil microbial populations with particular reference to the mineralisation/immobilisation processes.

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APPENDIX 1

Table 1: Fitted values for *a, b* and *c* in Eq. (7.10).

Slope	***A***	***b***	***c***
NE	1.18	0.221	1.411
NS	1.426	0.633	1.411
SE	0.80	0.214	4.561
SS	0.408	0.475	4.561
F	1	0	4.561