INVESTIGATING AND MODELLING THE DEPENDENCY OF PASTURE GROWTH ON SOIL SULPHUR AND PHOSPHORUS AVAILABILITY

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Keneti Faulalo

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ABSTRACT

A study was conducted in the lower North Island of New Zealand to evaluate new soil testing methods for diagnosis of sulphur (S) deficiency against pasture growth responses to applied S fertiliser, in the presence and absence of phosphorus (P) and nitrogen (N).

Field trials were conducted on eight sites at the AgResearch Hill Country Research Station at Ballantrae. The amounts of total soil S, P, and N at each site varied widely, caused by different superphosphate (SSP) fertiliser histories (low fertiliser input [LF] to high fertiliser input [HF]) and differences in grazing animal excreta return. Pasture growth on all of the eight plot trial sites chosen to represent a range of fertility levels, did not increase significantly to applications of S fertiliser alone (+S) (3 x 50kg S/ha as gypsum) over two years. Three LF sites did show significant increases in yields to application of S together with P (+SP, equivalent to SSP) (2 x 50kg P/ha as MCP). The +SP treatment was the most effective at promoting legume growth.

A suite of soil tests were designed and tested for their ability to extract sulphate S and labile organic S from soils. The amount of S extracted by a mixture of 4%H_2O_2 and 0.5M KCl [4%H_2O_2/$KCl_{(16hr)}$] (ranged from 50.7 - 105.3mg S/kg at a LF to a HF site) was found to be as good as the Olsen P test (ranged from 14.4 - 39.2mg P/kg soil) at predicting actual yields on unfertilised control plots (R^2 > 63% using several mathematical expressions). The 4%H_2O_2/$KCl_{(16hr)}$ and the Olsen P tests were also strongly correlated (R^2 = 77%). However, the 4%H_2O_2/$KCl_{(16hr)}$ was found to be better than the Olsen P test at predicting relative yield (RY) due to the application of a +SP treatment (R^2 = 60% and 19% respectively) probably because it has the ability to predict any S deficiencies that applied P would have induced. Only after basal S fertiliser was applied to the control did the Olsen P explain a similar percentage of the variation in RY (R^2 = 58%). As pasture growth was not singularly responsive to S, the ability of the 4%H_2O_2/$KCl_{(16hr)}$ test to predict S deficiency without P could not be tested.

The $4\%H_2O_2/KCl_{(16hr)}$ test was examined on a series of short-term trials established at nine locations in the lower North Island on different soil types and different climatic conditions. The fertiliser treatments on these trials included an S treatment (50kg S/ha as gypsum) with and without N (50kg N/ha as urea). A basal application of P at a rate of 40kg P/ha as MCP was also applied. Similar to Ballantrae, application of S on top of P (+SP) was the most effective at promoting legume growth (17 - 400%). Application of N caused detrimental effect on legume growth but did increase total pasture yield at all sites (14 - 83%).

Although the amounts of S extracted ranged from 59 to 156mg S/kg soil, this variation did not explain the variations in RY response to S at these sites, neither did the more traditional phosphate extractable S test (ranged from 4.1 - 10.5mg S/kg soil). The large range in RY suggest that basal P induced S deficiency on the control plots subsequent to soil sampling. For evaluation of the soil S test, an unfertilised control plot should have been included in the trial design. Failing to incorporate the interaction of S and P into the design of field experiments appear to be the main weakness in using RY as the pasture yield parameter for regression against soil test values. While efforts into improving soil tests for S are still required, it was concluded that the RY device is inadequate to normalise yields across sites because i) differences in yield potential caused by the interactions of soil fertility with climate could not be eliminated, and ii) estimates of yield potential vary with experimental designs.

To overcome these problems with RY, a mechanistic pasture growth model was developed to incorporate the effects of actual evapotranspiration (ET_a) on the relationships between pasture yields and soil fertility. It is assumed that climate can adequately be represented by rainfall, average temperature, and sunshine hours. A soil water balance model developed at Ballantrae, predicted daily soil water contents, drainage, and ET_a. Pasture growth dependency on ET_a and existing harvestable pasture mass were then modelled on a daily basis.

The model was developed from pasture yields derived from 2 and 4 weekly harvesting regimes throughout 1993. The ceiling yield ($Y_{ceiling}$) and ceiling growth rate ($g_{ceiling}$) values for each site that were estimated from these data, ranged from 662 - 2526 kg/ha and 7.1 - 30.3 kg/ha/mm respectively from LF to HF sites. Soil fertility as indicated by the Olsen P test explained much of the variation in $Y_{ceiling}$ (R^2 = 69%) and $g_{ceiling}$ (R^2 = 77%). The estimated maximum yield (Y_{max}) and maximum growth rate (g_{max}) values unconstrained by soil fertility were 3125kg DM/ha (R^2 = 69%) and 38.4 kg/ha/mm (R^2 = 77%). These values were considered too low because the 2 and 4 weekly data did not represent the full range of pasture growth normally represented in sigmoid curves. Nevertheless, the structural strength of the model was shown by both $Y_{ceiling}$ and $g_{ceiling}$ approaching Y_{max} and g_{max} at the same rate, controlled by $f_{1/2}$, the fertility level at which 50% of Y_{max} ($f_{1/2}$ = 23.0 mg P/kg soil, Olsen P) and 50% of g_{max} ($f_{1/2}$ = 22.5 mg P/kg soil, Olsen P) are obtained.

A better estimate of Y_{max} (8923 kg/ha) was obtained when yields harvested after a 9 week summer growth period was used to represent the ceiling yields at each site. As the dependency on soil fertility was the same, a g_{max} of 70 kg/ha/mm was estimated. These estimates were used to simulate pasture growth over variable harvest intervals from autumn 1990 to autumn 1992. The same parameter values were transferred to simulate pasture growth on sites in the east coast of the North Island. The seasonal variations in predicted harvested yields, closely resembled the patterns of yields measured through time. However, the actual yields predicted were generally lower than measured. The model therefore has structural strength but need extensive data for better estimates of initial parameter values.

This new approach, although require further development, emerges as a far better basis for understanding the relationship between pasture yields and nutrient supplies than regressions of soil tests against RY.

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CHAPTER ONE

INTRODUCTION

1.1 ASSESSING THE NEED FOR SULPHUR FERTILISER.

A study was conducted in the lower North Island of New Zealand to evaluate the interaction of sulphur (S) and phosphorus (P) nutrients in regulating the nitrogen (N) economy of grazed hill pasture systems. The study was initiated in the late 1980's in anticipation of a continued decreasing trend in the use of single superphosphate (SSP) fertiliser following the cessation of the New Zealand government fertiliser subsidy, in June 1986. It was conventional to attribute the widespread responses to SSP primarily to the P it contained and to assume that whatever S deficiencies that might exist, were eliminated by the use of this fertiliser. The increase in use of S free high analysis and slow release fertiliser products, led to the belief that the previously ignored S component of SSP was to become a key constraint factor on pasture growth thus, creating a need to develop efficient methods to assess S requirement of pastures.

The early approach to assessing sulphur (S) fertiliser requirements of pasture was to conduct field trials, then relate pasture production to fertiliser S application rates (eg., Lobb, 1954; Walker *et al.*, 1958; Blackmore *et al.*, 1969; During and O'Connor, 1975). This approach was resource intensive as it required large numbers of trial sites to represent a wide variety of soil types and climatic conditions. With a sufficient number of trials, it was considered possible to assess the effect of S application rates on pasture response patterns under varying conditions. This information was then used to extrapolate site specific field trial data to new situations for which an assessment was required. Both time and cost disqualify this approach as a solution to our current needs.

Since early 1980's, the S fertiliser requirement of New Zealand pastures has been estimated for a given soil group by using a computerised model which calculates S mass balances for various grazed pasture systems (Ministry of Agriculture and Fisheries-MAF, Soil Fertility Service-SFS, S model). The model assumes that total S input and total S losses, into and from the system, are in an approximate quasi-steady state (Sinclair and Saunders, 1984). The SFS in giving fertiliser advice, calculates the S requirements as equal to the net losses from the system, estimated from a knowledge of stocking rate, type of stock, topography, rainfall, and a soil group S leaching index (SLI).

The S requirement for maintenance calculated from the MAF-S model is modified according to the soil's ability to supply S and the stage of development of the pasture, which is then translated into a fertiliser recommendation. The ability of a soil to supply S is assessed by a soil test which measured the sulphate-S extractable by a calcium phosphate solution. Among other factors, the fertiliser recommendation is highly dependent upon this extractable sulphate-S as an index of soil S status.

1.1.1 **Problems Assessing Soil S Status**

Phosphate extractable sulphate-S is widely recognised as the fraction of soil S which is available for immediate plant uptake. However, soil tests that extract this soil fraction in soils, explain less than half of the variation observed in pasture response to S fertiliser, over a wide range of pasture soils varying in their fertiliser histories and management (Sinclair *et al.*, 1985; Saunders *et al.*, 1988).

Firstly, soil sulphate-S values can change markedly during the year due to fertiliser application, mineralisation, immobilisation, leaching, and plant uptake (Sinclair *et al.*, 1985; Ghani *et al.*, 1990). Secondly, extractable sulphate-S soil test does not estimate net mineralisation rates measuring the plant available S or 'replenishing power' of the soil, replenishing the S lost via plant uptake and leaching. This is because the extractable sulphate-S test does not include the significant amounts of labile organic S, which are the main short term reserves of mineralisable S in soils.

In recognition of the amount of mineralisable organic S accumulated during pasture development, a 'Pasture Development Index' (PDI) is used along with the extractable sulphate-S soil test value in the MAF-S model to estimate more accurately the S fertiliser requirement of the soil (Sinclair and Saunders, 1984). The PDI is regarded as an estimate of the accumulated organic S in the soil with time, after initiation of regular superphosphate use (Perrott and Sarathchandra, 1987; Nguyen *et al.*, 1990; Saggar and Hedley, 1989, 1990a; Haynes and Williams, 1992). It is defined as the product of the time since pasture was introduced over natural vegetation, the average stocking rate over the same period, and a paddock contour factor (Sinclair and Saunders, 1984). The problem with PDI acting as an index of organic S mineralisation in the MAF-S model is that it is a dimensionless term that is reliant on farm records, which are often uncertain.

In an attempt to find a better soil test that accurately represents the ability of the soil to supply S, it was thought that a soil test which incorporates a labile organic S fraction would be preferable to the extractable sulphate-S soil test in conjunction with a PDI. Recent studies in this direction include that of Watkinson and Perrott (1990) who proposed that the organic S fraction extracted in the same calcium phosphate extractant that extracts sulphate-S, is a more accurate test for S status of soils. Watkinson *et al.* (1991) reported a relationship between this proposed measure of mineralisable organic S and PDI and suggested that the extractable organic S measured should provide the basis for more reliable fertiliser advice. Since that time, Watkinson and Kear (1996) moved away from the use of calcium phosphate and proposed that the organic S extracted with 0.02M potassium phosphate correlated better with pasture response to S, than the organic S in 0.02M calcium phosphate. Another recent soil test for mobilising organic S, involves heating the soil in 0.25M potassium chloride at 40°C for 3hr (Blair *et al.*, 1991), based on a method for labile organic nitrogen (Gianello and Bremner, 1986).

The implied logic behind the regression of pasture S response to these soil S tests, is that the amount of S required as fertiliser is negatively related to the quantity of S supplied by the soils. The amount of S fertiliser required is then, the difference between the amount of S required by pasture plants and S supplied by the soil. The problem is that, while a soil S test may be very accurate at assessing the ability of the soil to supply S (index of S availability), the present methods for determining S requirement of pasture are unsatisfactory if, i) the amount of available water change, and ii) the amounts of other nutrients change, eg., phosphorus (P) and nitrogen (N).

1.1.2 **Problems Assessing Pasture S Requirement, Using Relative Yield**

The most commonly used method to normalise pasture S requirement at different sites (ie., different amounts of water available and different quantities of other nutrients) is by expressing the yields in each of the various experimental sites as percentages of a maximum yield, ie., as *relative yield* (RY):

$$\frac{\text{Yield of control treatment}}{\text{Maximum yield obtainable with applied nutrient}} \times \frac{100}{1} .$$

A relationship is then sought between a measure of S availability, such as a soil or plant test value which varies from site to site, and the calculated RY. Among other problems with this approach, the relationships between plant response to applied fertiliser and soil tests is much more complex for grazed legume based pasture than for annual crops.

For annual crops, a single yield is generally obtained as a measure of response to fertiliser, eg., Fixen and Ludwick (1983) for alfalfa, Holford *et al.*(1985) for wheat, and Mallarino and Blackmer (1992) for corn. As Grigg (1972) pointed out, "permanent grass-clover pastures under grazing do not provide a single index of response because pasture production is continuous, but rate of growth varies with seasonal and climatic factors, so it is not possible to fix an absolute time after topdressing to measure pasture yield response to a fertiliser". Therefore, combining the results of pasture yield data by the RY device is questionable for testing the significance of regressions with soil tests because the deviations from the overall regression line contain different types of errors - some of it within experiments and some of it among experiments.

Perhaps the most fundamental weakness of RY is that it does not provide a basis for estimating economic fertiliser rates. Farmers derive their income from absolute yields and must justify their expenditures for fertilisers on the basis of economic returns from absolute increases in yields. While RY of course can be converted to absolute yields, the absolute yields corresponding to a given RY may vary widely. Thus, problems associated with farmers estimating likely yield increases due to added S fertiliser is only postponed by calibrating rates of fertiliser S application or soil test values to RY.

In summary, the problems limiting our current understanding of the relationship between pasture yield and soil S status include, i) the reliability of the measure of soil S status, and ii) the validity of the RY device being used to estimate pasture S requirement in varying climatic conditions and availability of other nutrients.

The precise meanings of the words 'available' and 'availability' are often not agreed upon despite their common use to describe the supply of plant nutrients in soil. For purposes of discussion in this thesis, the term 'availability' is used to describe the ability of the soil to supply *effective quantities* of nutrients, while the word 'available' will mean *susceptible to absorption* by plants.

1.2 THESIS OBJECTIVES

The initial objectives of this thesis were:

i) to find an improved soil test to estimate the ability of the soil to supply S,

ii) to estimate pasture S requirement as affected by the availability of P and N,

iii) to develop a better framework than regressions using RY, to predict actual pasture yields in variable climatic conditions.

To meet these objectives, field trials were established on a soil fertility development sequence of pasture farmlets at DSIR Grassland (now known as AgResearch Grassland) Research Station at Ballantrae, from autumn 1990 to autumn 1992. The soils are of similar soil type and are under similar climatic conditions, but with different SSP fertiliser histories. The fertiliser treatments on the plot trials were designed to investigate the responsiveness of pasture to the interactions of S with P and/or N. The yield data from these trials are reported in Chapter Three. From the patterns of pasture yield responses observed, a conceptual model is presented to develop further understanding of the interaction between the availabilities of soil S and P, regulating the N economy of the swards. Ball and Field (1987) noted that, "despite the best effort by farmers and agricultural scientists, a chronic N deficiency was seen to persist in well-managed pastures, even decades after sowing". The emphasis on N as the primary limiting factor is therefore, well justified.

In Chapter Four, the soils samples collected at the beginning of the trials were extracted for different fractions of soil S, using several chemical extraction techniques. A theoretical basis for the extraction of soils for both sulphate-S and labile organic S, as an index for S availability is proposed. The soil S fraction extracted in each chemical extractant investigated, are ranked against each other by regression analysis, using mean annual accumulated yields on the unfertilised control plots. They were also ranked against the Olsen P test. The mean yields on the unfertilised control plots were accumulated annually to eliminate seasonal variations. This allowed for an investigation on the effects of soil supply of S on pasture yields only. The differences in climatic conditions from one year to another however, could not be removed.

The best soil S extractants from Chapter Four are used to predict the responsiveness of pasture to applications of S, P, and/or N fertilisers, using RY as the pasture yield parameter in Chapter Five. Despite the problems associated with RY to indicate pasture requirement for a nutrient, the need to understand the interaction of S and P, and to isolate each nutrient as a growth factor, makes the use of RY worth investigating. The soil S tests proposed from Chapter Four, are also compared with the Olsen P test.

Another short-term series of field trials were also established to investigate more specifically, responses to S in the presence and absence of fertiliser N, on different soil types and climatic conditions. The soils from this series of trials were tested for the amounts of extractable S, using the most superior of the soil tests investigated in Chapter Four. The amounts of extractable N in the same extractant were also analysed for to investigate the potential of the proposed extractants to be used as bi-nutrient soil tests.

Even with the best understanding of how the interaction between the availabilities of soil S and P, regulates the N economy of pasture swards, the constraint placed by climate on pasture growth will ultimately limit the use of regressions between RY and soil test values as diagnostic tools to estimate fertiliser requirements. Establishing relationships between pasture yields and quantitative measures of climate is vital before the effect of soil fertility can be accurately assessed. In Chapter Six, a pasture growth model as affected by climate is developed. In this model, climate is assumed to be adequately represented by rainfall, maximum and minimum temperature, and sunshine hours. These climatological data are used to compute daily amounts of available water that pass through the plants as actual evapotranspiration, using a soil water balance model. The incremental increase in daily yield is then computed as a function of both the amount of water available as actual evapotranspiration, and the amount of pasture mass that was standing as cover at the beginning of each day. The yield data used to develop this model were measured from January 1992 to January 1994, using 2 and 4 weekly harvesting regimes. The efficiencies of how pasture uses this available water at different levels of pasture masses, standing as cover, are then modelled for their dependency on the fertility of the soil as measured by the Olsen P test.

In Chapter Seven, parameter values estimated, using both the Olsen P and the proposed soil S test are used to simulate pasture growth at variable harvesting periods that were measured in the trial series between autumn 1990 to autumn 1992, reported in Chapter Three. The same parameter values obtained at Ballantrae are also investigated if they could be transferred away from Ballantrae to some sites at the East Coast of the North Island in the Wairarapa.

Firstly, to develop further understanding of S cycle in grazed pasture systems, the literature is reviewed in Chapter Two. Apart from the nature and transformation of S, the literature review also describes the important features of New Zealand legume based pasture and their management as they impact on the topic of this thesis. It will also serve to highlight that pasture S requirement is affected mostly by the availability of P and N more than all other nutrients. As most of this thesis is devoted to the development of models to predict pasture yield as affected by soil fertility, a discussion of the principles of modelling is also presented to introduce the logic behind the approaches taken in this thesis.

During the progress of this study, new insights into the dependency of pasture growth on soil fertility were discovered. Consequently, improvements in the design of field experiments are often seen only from hindsight. In this thesis, the emphasis is placed upon developing concepts and identifying new problems during the development of models, rather than complete representation of real systems. Therefore, while the outcome in some efforts may not be as expected, the desire to develop further understanding of the relationships between nutrient supplies and pasture yields is the underlying force in the attempts. The success of current research is judged by whether the unexplained result allows future research to be more clearly defined. Chapter Eight summarises the outcomes of the research studies taken here and recommends some direction for future research.

CHAPTER TWO

REVIEW OF LITERATURE

This literature review is in three parts. The first part (section 2.1) is to describe the important features of New Zealand legume based pastures and their management as they impact on the availability of soil S, in particular the role of S fertiliser relative to P and N fertilisers in the development of pastures. The second part (sections 2.2 - 2.4) is to summarise research findings available on the S cycle in a soil-plant-animal system and to illustrate why the approaches taken for this research were chosen. The third is to discuss the principles of modelling as most of this thesis is devoted to the development of models. It is hoped that at the end of this literature review, the approaches taken would be justified to improve our understanding of the dependency of pasture growth on the availability of soil S.

2.1 BACKGROUND TO SOIL FERTILITY IN NEW ZEALAND LEGUME BASED PASTURES

In New Zealand, pastoral agriculture is based on the grass-legume association. Symbiotically fixed nitrogen (N) is relied upon directly to provide the substantial inputs of N required to build and sustain soil fertility for intensive grassland farming. High herbage production levels are the heritage of large inputs of phosphate (P) and S based fertilisers, which have encouraged introduced legumes and increased soil N availability by fixing 55 to 85 kg N/ha/yr (Ledgard and Brier, 1987).

As early as the 1880's, insufficient P supply during pasture development was identified as a major constraint to legume growth. From the 1920s to the late 1970s, superphosphate (SSP) was the common form of fertiliser P used in New Zealand agriculture. The processes involved in the manufacturing of SSP include the acidulation of high grade phosphate rock (PR) from the Indian and Pacific Oceans with sulphuric acid which supplied New Zealand farmers with plant available P. Superphosphate incidentally met the annual S requirement of pasture in many environments. It was not until the 1950s that the previously ignored S component of SSP was itself established as an important plant nutrient (Walker, 1955), particularly in strongly leaching environments with low anion exchange capacity and in soils with low reserves of S in soil organic matter.

Walker and Adams (1958b) concluded that during pedogenesis, the P content of the parent material controlled N, S, and organic matter contents of soil because, C and N are added biologically, while S can be absorbed from the atmosphere or enter as precipitation. In line with these conclusions, increasing soil P status with fertiliser also has a marked impact on soil organic N, S, and P levels (Walker *et al.*, 1959). It was also proposed by McGill and Cole (1981) that inorganic P supply, strongly controls the gross dynamics of a terrestrial biological system, while C provides an energy source to control internal cycling and is associated with N, S, and organic P. It is therefore obvious that, in order to study the role of S as a contributing control factor to the dynamics of pasture growth, its interaction with P is the most important part.

2.1.1 **Trends of Fertiliser Use in New Zealand**

In June 1986, the New Zealand government ceased it's subsidy for fertiliser price. The resultant fall in farm revenues led to a downturn in the quantity of fertiliser applied by New Zealand farmers (Fig. 2.1). In the late 1980's, fertiliser use was about 50 to 65% of that in the late 1970's. The increased profitability of dairying enabled fertiliser usage to increase over the past few years, a trend that started in 1991, with total fertiliser application increasing by around 100,000 tonnes from 1990 to 1995.

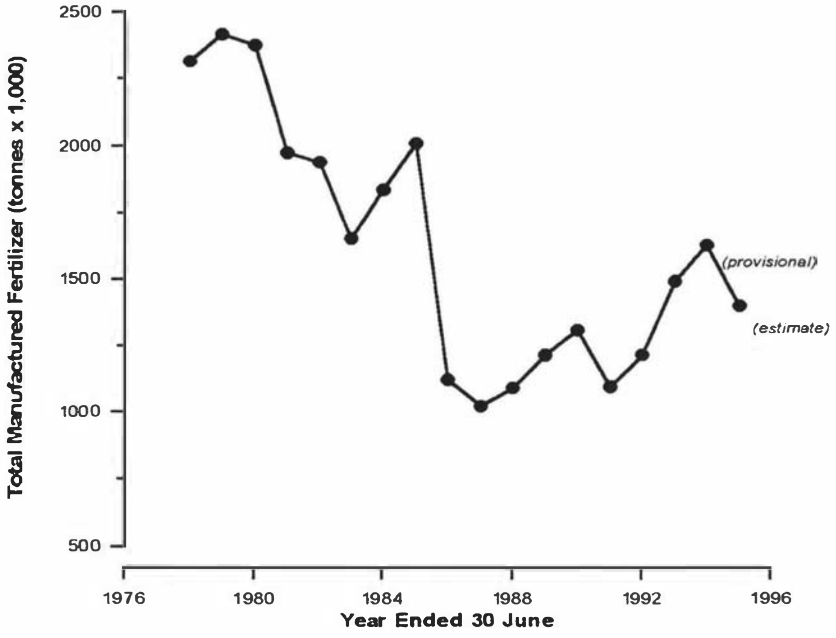

Figure 2.1 Manufactured fertilisers sold by Fertiliser Works in New Zealand from 1978 to 1995. [Source: *Situation and Outlook for New Zealand Agriculture* (1995). pp.100. MAF Agriculture Policy, Wellington.]

Fertiliser use in New Zealand is dominated by the requirement of the 14 million hectares of legume based pastures. Pastures in this study occur in an aquic (USDA soil taxonomy) regime, i.e., rainfall generally exceeds evapotranspiration and drainage occurs.

Superphosphate is still the predominant fertiliser used for grassland and crops, but a greater range of products, particularly S free high analysis or slow release fertilisers have become available to farmers. In the early 1980s, around 95% of total fertiliser sales were SSP or mixes of SSP. This fell to 75% in 1993. (*Situation and Outlook for New Zealand Agriculture* (1994). MAF Agriculture Policy, Wellington). The dominant position of S and P fertilisers also is consistent with the recommended fertility maintenance of legume based pastures. The total amounts applied per hectare indicate that currently much pasture is receiving below the recommended rates of maintenance fertiliser.

While the increase in the profitability of dairying in the past few years has seen the use of above-maintenance inputs of nutrients in S and P fertilisers, the sheep and beef sector continued to experience only average levels of farm income, limiting nutrient input level (*Situation and Outlook for New Zealand Agriculture* (1995) MAF Agriculture Policy, Wellington). The need for accurate assessments of the nutrient status of these soils remains a major priority, as a means for ensuring the optimum use of applied fertilisers. In this regard, the need to improve the ability of a soil S test to more accurately assess the S status of a soil and the links between S and P availability and legume growth is paramount. Legumes remain the major sector for N inputs.

2.1.2 Pasture Development and Steady-State Systems

Ecological perspective, covering stages in the development of productive pastures from regrassed grassland (Sears, 1956; Levy, 1970), formed the basis for much of our understanding of competitive relationships in pastures, pasture management, potential herbage yields, and species' contribution to yield (Fig. 2.2).

Studies into the dynamics of soil organic matter during pasture development (Walker *et al.*, 1959; Jackman, 1964) have shown that organic matter and its contained nutrients accumulate below well managed pastures up to an equilibrium or steady-state level for that ecosystem (Climax stage, Fig. 2.2). While the build-up of soil N may be used as a measure of the fertility of soils (or the depth below the baseline in Fig. 2.2), by means of soil testing (eg., Quin *et al.*, 1982; Jones, 1985), these measures of N availability cannot explain potential yields for all circumstances and among different years because the contribution of N fixation to growth in any set of circumstances and in any one year, is also affected by S and P availabilities in the soil affecting N inputs by legumes. It has also been shown that increasing the amounts of available N by applying N fertiliser, reduces the amounts of N fixed (Crush *et al.*, 1982; Ledgard and Saunders,

1982) hence, a reduction of the efficiencies of S and P availabilities at promoting legume growth. These interactions of S, P, regulating the N economy of the swards and affecting rates of pasture growth, makes it difficult to measure soil fertility quantitatively, even if the build-up of soil N and N availability itself could be measured.

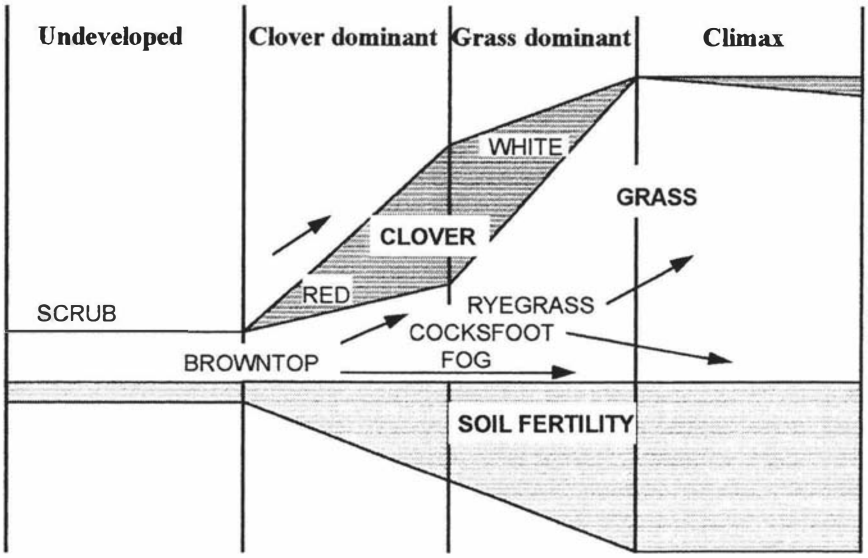

Figure 2.2 Diagrammatic representation of development of pasture and soil fertility, adapted from Sears (1962). Annual pasture production is shown as height above, and soil fertility as depth below the base line. Re drawn from Ball and Field (1987; pp. 91)

The build up of organic matter and the nutrient it contains as a result of SSP applications is the main source of S and P soil supplies. Conventionally, the widespread responses to SSP is attributed primarily to the P it contains and to assume that whatever S deficiencies might exist are eliminated by the use of SSP. The ability of the soil to supply P at the different stages of pasture development is commonly measured by the Olsen P soil test. However, pasture responses to SSP fertiliser are often observed on soils with high Olsen P values (Cornforth and Sinclair, 1984). While this is often attributed to high-P sorption properties of some soils (Hedley *et al.*, 1995), the S component of SSP fertiliser is generally under-estimated.

In the inorganic form (SO_4^{2-}), S has a weaker binding capacity to soil sorption sites than P, hence S is more prone to leaching than the buffered P (Bolan *et al.*, 1988). This view is supported by recent research showing that grazed pasture systems are inherently S leaky (Saggar *et al.*, 1990a, 1990b; Haynes and Williams, 1991; Sakadevan *et al.*, 1993) with amounts equivalent to 40 - 70% of the annual application of fertiliser (15-45kg S/ha/y) being lost by leaching. Lambert *et al.* (1988) also reported data that showed the S reserves resulting from previous regular SSP applications, were far less than the P reserves which led these authors to suggest that S rather than P should first limit pasture production if regular SSP fertiliser inputs were discontinued.

2.2 NATURE OF SULPHUR IN SOIL

Soil is one of the most complex mixtures on this planet, not only from a biological, but also from a physical and chemical viewpoint. Consequently, the questions regarding the removal and replenishment of S in soils cannot be totally answered because it is impossible to develop an analytical technique to study the nature of soil S that leaves the soil fabric undisturbed. Without the identification of specific S compounds in soils, the common approach is to classify groups of S compounds into general forms allowed for by current extraction and analytical techniques.

2.2.1 **The Forms of S in Soil**

Most agricultural soils or mineral soils have total S contents ranging from 50 to 1000mg/kg in the surface 15cm (Freney and Williams, 1983; Syers and Curtin, 1987). The New Zealand Soil Bureau reference topsoils have total S values of 1120-

1630mg/kg for Yellow-brown loams, and 130 to 630mgS/kg for other soils (New Zealand Soil Bureau, 1968). Ghani *et al.*, (1991) reported a total S value of 930mg/kg for the topsoil of the Horotiu Yellow-brown loam under pasture, a value below the New Zealand Soil Bureau reference soils for Yellow-brown loams, and values ranging from 185 to 615mg/kg for other soil types, within the New Zealand Soil Bureau reference soils. In contrast, Perrott and Sarathchandra (1987) in their work with soils under established pasture, reported total S values that were generally 20% higher for the same soil groups with mean values of 1570mg/kg for the Yellow-brown loams and 550mg/kg for the other soils excluding recent and organic soils. These workers presumed that the higher soil S contents reflected histories of greater superphosphate application to soils in their survey.

The proportions of S in organic or inorganic form vary according to soil type (Metson, 1979a; 1979b), depth in profile (Williams, 1974; Haynes and Williams, 1992), climate and cultural conditions (Bettany *et al.*, 1979, 1980). In most soils, more than 90% of the S is organic and is unavailable for plant uptake until it has been mineralised (decomposed by soil organisms) to inorganic S. In situations where inputs of S from other sources are very low, organic S is the main source of plant available S (sulphate-S) in soil (Bettany *et al.*, 1980; Freney 1986).

2.2.1.1 *Plant Available S (Sulphate-S)*

Sulphur is absorbed by plant roots almost exclusively as sulphate-S (SO_4^{2-}), thus the influence of other components in the S cycle (Fig. 2.1) on this pool are of great importance. This S fraction however, represents only a relatively small proportion of total S, generally less than 5% in New Zealand pastoral soils (Perrott and Sarathchanda, 1987; Ghani *et al.*, 1988; Sakadevan, 1991).

Sulphate-S is derived from wet and dry deposition of mainly sulphate-S and sulphur dioxide, weathering of soil parent rocks (oxidation of reduced inorganic forms of S, eg. sulphide) and mineralisation of organic S (Roy and Trudinger, 1970). Weathering reactions are thought to be a minor input of S in current topsoils (Metson, 1979a), mainly because mineral sulphides are quickly weathered in aerobic, topsoil environments.

The soil sulphate-S fraction includes the readily soluble inorganic sulphate-S as well sulphate-S adsorbed to soil colloids. In most soils, adsorbed sulphate-S is readily available to plants through desorption and is the main source of plant-available S (Barrow, 1967; Barrow, 1969; Hasan *et al.*, 1970; Westerman, 1974). Soils high in amorphous iron and aluminium oxides or allophane have considerable capacity to sorb sulphate-S through anion exchange sites (Barrow, 1969), which becomes less available for plant uptake. In soils with low phosphate retention (less than 70%), adsorbed sulphate-S may accumulate during periods of slow plant growth and/or minimal leaching, and decrease during periods of vigorous plant growth and/or leaching (Nguyen and Goh, 1990).

Soil sulphate-S levels are often subject to seasonal fluctuation depending upon the net balance between addition from rainfall, irrigation water, mineralisation of organic matter, applied fertilisers, and losses from leaching, plant and micro-organism uptake (Williams, 1968). The importance of these processes are reflected in the data of many workers such as Nguyen (1982), Goh and Gregg, (1982a, 1982b) Cornforth *et al.*, (1983), Nguyen *et al.*, (1989a, 1989b), and Ghani *et al.* (1990). In the North Island, the amounts of extractable soil sulphate-S present in spring are generally lower than in autumn, possibly due to the increase in leaching loss of sulphate-S and the slow rate of mineralisation during the winter time (Nguyen, 1982; Nguyen *et al.*, 1989a, 1989b; Cornforth *et al.*, 1983). Ghani *et al.*, (1990) found that amounts of soil sulphate-S can decrease in short spaces of time, particularly, after rainfall events causing drainage.

Short-term Variability vs Long-term Steady-State of the sulphate-S pool.

Soil sulphate-S pool size varies significantly over short periods of time (Blair 1979). However, in the absence of external inputs of sulphate-S, and with steady removal by leaching and transfers by plants and animals, Watkinson and Perrott (1990) postulated that a quasi steady-state exists in soil producing relatively constant concentrations of sulphate-S. The results of Ghani *et al.*, (1990) showed variability with season in the amount of soil sulphate-S, but also illustrated that in constant soil conditions (eg. absence of recent fertiliser application and heavy rain), sulphate-S was steady within 1mg S/kg for several months due to the significant amounts of sulphate-S released by mineralisation. Such results indicate the magnitude and speed of mineralisation processes operating under field conditions.

In some grazed pasture systems, a total of 15 to 30kg S/ha may be lost from the system, via the sulphate-S pool each year (Saggar *et al.*, 1990b; Sakadevan, 1991). For steady-state conditions to apply, mineralisation must equal the sum of immobilisation plus leaching and plant uptake. For the system to reach and sustain steady-state, regular S fertiliser applications are required.

2.2.1.2 ***Organic S***

From the preceding discussion, it is obvious that the nature of organic S and the dynamics of the mineralisation/immobilisation processes, is central to predicting plant uptake and leaching losses. However, little is known of the macro-molecular nature of organic S in soils (Freney and Stevenson, 1966; Freney, 1967; Freney and Williams, 1983). Organic S mainly originates as plant and animal residues which are subsequently decomposed and re metabolised by soil microorganisms. Freney (1967) and Lowe (1969a, 1969b) reported a wide variety of S compounds that were produced by organisms either in or on soils. Most of these were susceptible to decomposition, did not accumulate in their mono-molecular form, and were not readily identifiable in the soils.

Although more than 90% of total S may be present in the organic form, on an annual basis, only a small percentage of this fraction, as little as 2%, may enter the active S cycling pool which supplies S, available for plant uptake (Till and May, 1971; Goh and Gregg, 1982a, 1982b; Chapman, 1987a, 1987b).

Under long-term grassland, there can be a build up in organic matter content whilst, in contrast, under arable cultivation there is appreciable breakdown of soil organic matter (Jackman, 1964; McLaren and Swift, 1977; Keer *et al.*, 1990; Haynes and Williams, 1992; Hedley *et al.*, 1995).

Sulphur in soil organic matter or extracts of soil can be separated into two major groups, (i) HI-reducible S, and (ii) C-bonded S, based on susceptibility to reduction by reducing agents. Such fractionation indicate the chemical form of S, but produce little if any information about the size or nature of the 'labile pool' (rapidly cycled pool) of mineralisable organic S present in the soils (Haynes and Williams, 1992) and therefore have not been very successful for predicting S mineralisation rates (Freney, 1986).

Plants (*Sorghum vulgare*) were found to utilise S from both the HI-reducible as well as the C-bonded S fractions (Freney *et al.*, 1975). Incubation experiments using labelled S (^{35}S), show that both HI-reducible and C-bonded S fractions can be transformed to sulphate-S via mineralisation (eg., Bettany *et al.*, 1974; Goh and Tsuji, 1979; Fitzgerald *et al.*, 1984; McLaren *et al.*, 1985; Strickland and Fitzgerald, 1985; Ghani *et al.*, 1988). Similarly ^{35}S labelled SO_4^{2-} enters both soil organic S fractions when soils are incubated (McLaren *et al.*, 1985).

HI-reducible S

HI-reducible S compounds include S atoms that are not directly bonded to C but are linked to C via an oxygen atom (C-O-S, ester sulphate-S), or nitrogen atom (C-N-S, sulphamate). This fraction is thought to be generated predominantly by soil micro-flora (Fitzgerald, 1978; David *et al.*, 1984;) which metabolise organic residues in the presence of adequate S (Saggar *et al.*, 1981b). Mechanisms of ester formation, transformation, and its significance in the S cycle were reviewed by Fitzgerald (1976). However, what proportion of organic sulphate-S are metabolic by-products, components of dead cells, or products formed by reaction of inorganic sulphate-S with humic constituents, remains unclear.

Organic sulphate-S are thought to be associated with mainly the higher molecular weight fraction of soil organic matter (Bettany *et al.*, 1973; Schoneau and Bettany, 1987; Swift *et al.*, 1988; Keer *et al.*, 1990; Haynes and Williams, 1992), and are considered to be the most labile fraction. Bettany *et al.* (1973) suggested that higher degrees of humification as a result of increased biological activity, will form higher molecular weight, strongly condensed stable humic acids with considerably active, hydrolysable side chain components. Thus residual organic S in soils reflects a fraction which has been protected from microbial decomposition, either spatially protected within aggregates or associated with complex organics.

Carbon-bonded S

C-bonded S is believed to be more associated with the highly condensed aromatic humus core and a more stable organic S form than the organic sulphate-S fraction (Bettany *et al.*, 1973; Bettany *et al.*, 1979). This S fraction is normally calculated as the difference between total organic S and organic sulphate-S. Soil C-bonded S may be derived directly from both leaf litter and root inputs, as well as microbial protein synthesis.

C-bonded S can be fractionated into two groups, (i) Raney-Nickel reducible organic S, believed to be mainly amino acid S (Lowe and DeLong, 1963; Freney *et al.*, 1975) and, (ii) 'inert' C-bonded S fraction which is highly resistant to chemical degradation, and is probably not a significant source of plant-available S (Biederbeck, 1978).

2.2.1.3 ***Microbial Biomass-S***

Soil microbial biomass is a living part of soil organic matter, and with plant roots, are the driving force behind mineralisation/immobilisation processes in soils. The microbial biomass-S fraction compromises only *c.* 0.4 to 4% of total S (Saggar *et al.*, 1981a; Chapman, 1987a; Gupta and Germida, 1988a; Ghani *et al.*, 1990).

Soil moisture and temperature are factors that influence microbial activities and consequently, soil microbial biomass-S concentrations (Ghani *et al.*, 1990). Degradation of soil organic compounds where S is a constituent is controlled firstly, by the energy needs of the microbes which they can obtain from energy released when C is respired and secondly, by the S requirements of the microbes for metabolic, structural and/or other physiological needs. The enzymatic activities of microorganisms in the degradation of soil organic S compounds would be difficult if not impossible to relate with S mineralisation rates because of the unknown identity of all the selective and non-selective enzymes involved in degradation. In addition, substrate accessibility is complex and probably one of the more important factors in the undisturbed soil fabric.

2.3 SULPHUR TRANSFORMATIONS IN SOIL: A SULPHUR CYCLE

Understanding the S cycle in soil-pasture-animal systems is essential in defining pasture S requirements as well as proper definition of soil S status or S availability. Although organic S is the main reservoir of S in soils, it is the size of the highly mobile plant available soil sulphate-S pool that is central in the definition of soil S status. The amounts of S as sulphate-S together with the water content of the soils, determine the S concentration of soil solution. Understanding the processes that regulate the size of the sulphate-S pool and factors affecting these processes will enable us to incorporate the cycling of S nutrient into an integrated framework proposed in chapter one for optimising the use of fertilisers.

The S cycle presented in Figure 2.3 was designed to identify the components of S pools and the processes of S flow between these components in a soil-plant-animal grazing system. As mentioned in the previous section, the best researchers could do in identifying the components of a S cycle, has been to classify the groups of S compounds into general forms allowed for by current extraction and analytical techniques. However, these general forms produce little or no information on the 'active pool' of soil S which regulates the incorporation of inorganic S into (immobilisation) and the release of S, from (mineralisation) organic matter, because the active-S pool itself consist of all the general forms of S identified in section 2.2. The aim in presenting the S cycle in Figure 2.3, is to summarise appropriate research that have been published in the literature with the hope of identifying a level of detail required to study S in pasture systems. Figure 2.3 depicts an oversimplified view of S transformations in the soil because in reality, S flows and transformations are not only cyclic, but interrelated processes that are interwoven into a network.

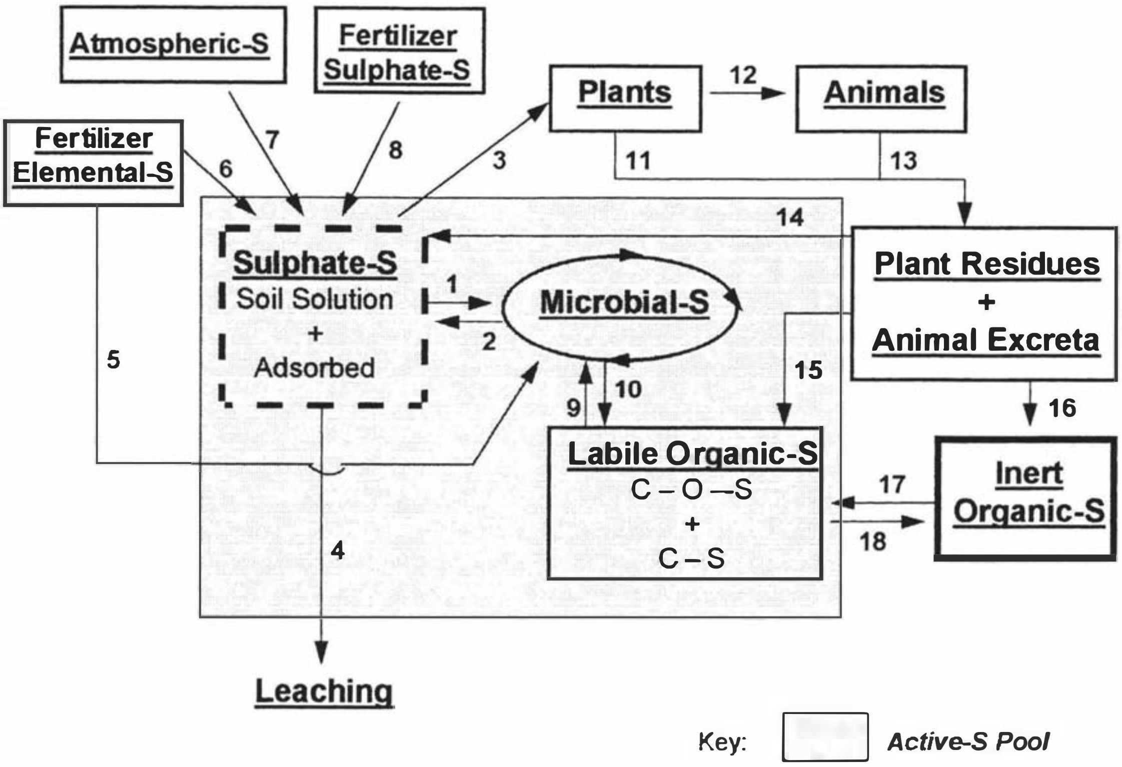

Figure 2.3. The various components of the S cycle and the processes that determine the size of the plant available sulphate-S pool. 1. Microbial assimilation and immobilisation of sulphate-S. 2. Mineralisation. 3. Plant uptake of sulphate-S. 4. Leaching. 5. Biological oxidation of applied elemental-S. 6. Chemical oxidation of applied elemental fertiliser S. 7. Atmospheric input of sulphate-S. 8. Applied sulphate-S fertilisers. 9. Release of labile S by microbes. 10. Microbial assimilation of labile organic S. 11. Dead root material and residual plant litter. 12. Animal intake of S via pasture. 13. Animal residues and excreta. 14. Sulphate-S in urine and dung; Sulphate-S not used in protein synthesis in plants return to the soil as sulphate-S. 15. Labile S released during decomposition. 16. Humification and/or stabilisation of resistant plant residues. 17. Organic matter turnover due to other environmental factors such as drying and wetting, freeze and thaw cycles, and possibly decomposition by microbes. 18. Immobilisation of labile organic S.

The driving force regulating soil sulphate-S levels is microbial biomass. Factors affecting microbial ecology as well as population dynamics will affect the turnover of S into and out of the labile organic S pool. It was reported by Gupta and Germida (1988b) that addition of elemental S fertilisers decreases populations of predatory protozoa while amoebal grazing of bacteria enhances organic S mineralisation.

There are seven possible inputs into the active-S pool. Over the last few years, process 6 is increasing in popularity as more farmers turn to elemental S as an alternative source of S, however, SSP is still the predominant fertiliser (process 8). Saggar and Hedley (1989), using a detailed geographic analysis of input variations according to rainfall and distance from the sea, estimated the atmospheric input of S in New Zealand (process 7) as 64,000t.

There are three outputs from the active-S pool; plant uptake (process 3), leaching losses (process 4), and immobilisation of labile organic S to inert organic S. The term inert is used loosely here because S incorporated into this pool are potentially mineralisable (process 17), but at a much slower rate compared to the mineralisation of labile organic S (process 9).

2.3.1 Leaching Losses

Accumulation of organic S in pasture soils is enhanced when annual occurrence of superphosphate application (process 8) (Nguyen and Goh, 1990; Haynes and Williams, 1992) increases C and N fixation. However, Nguyen and Goh (1990) observed that when the rate of sulphate-S application was increased from 21 to 42kg S/ha, the accumulation of organic S did not increase. They calculated that approximately 50% of additional S was not taken up by plants (process 3) or immobilised (process 1) and was considered to be leached (process 4). Liebig's law of minimum limitation must apply and a further factor other than soil S status limited pasture production and efficient utilisation of extra S added. Haynes and Williams (1992) observed similar results where applications of 188 and 376 kg/ha superphosphate resulted in similar total organic S contents of soil. They observed that further accumulation of organic S with increase in superphosphate application rate was limited by the lack of organic-C accumulation in the 376 compared to the 188 treatment and the S unaccounted for was probably lost through leaching.

Saggar *et al.* (1990a,b), using a nutrient transfer model in a hill country pasture calculated leaching losses from superphosphate fertilised pasture soils of low (<60%) and high (>85%) P retention capacities to be in the order of 20 to 70% and 14% respectively, of the sulphate-S applied depending upon fertiliser application rate. Smith *et al.* (1983) calculated a drainage loss of 15kg S/ha from tile drains in their study on a yellow grey earth soil fertilised the same year with 43kg S/ha as superphosphate compared to a loss of 9kg S/ha from the unfertilised soil indicating an apparent leaching loss of 10.4% of the applied S. On a mole-tile drained soil of low P retention with a Sulphur Leaching Index (SLI) (Cornforth and Sinclair, 1984) of 5, Heng *et al.* (1991) measured drainage losses of 9 and 17kg S/ha/yr during two consecutive years from a pasture fertilised in the autumn with superphosphate. Heng *et al.* (1991) also showed that leaching losses from pasture fertilised with triple superphosphate plus elemental S (processes 6 plus 8) under the same conditions were only 3 to 4kg S/ha/yr suggesting that drainage losses of S could be reduced at least in the short term (1 to 2 years) by applying elemental S rather than SSP in autumn.

Goh and Nguyen (1991) suggested that the leaching of sulphate-S in urine patch areas is the major loss mechanism for S from pasture soils, due to the relatively high concentrations of sulphate-S accumulated in urine patches (Williams and Haynes, 1990). On the other hand, Sakadevan (1991) using field lysimeters studies on farmlets with two fertiliser histories (HF=375kg SSP/ha/yr for 14 years and LF=125kg SSP/ha/yr for 14 years) found that leached S was dominantly derived from the mineralisation of soil S (processes 2, 9, and 17) even in sheep urine patches. In all, 34.4 and 58.0% of the mineralised soil S in the LF and HF farmlets respectively were leached over a period of ten months (Jan. to Oct. 1990).

In summary, the factors that affect leaching losses are: (i) amount and timing of rainfall (Heng *et al.*, 1991), (ii) soil water holding capacity (Gregg and Goh, 1979), (iii) soil sulphate-S retention (Hogg and Toxopeus, 1966; Gillman 1973; Gregg and Goh, 1978; Gregg and Goh, 1979), but this will be dependent upon the rate of S application or excreta deposition (Saggar *et al.*, 1990a,b; Hedley *et al.*, 1990), and (iv) timing of fertiliser application. For example, fertiliser application in drier, warmer periods when plants grow rapidly results in less leaching losses than autumn applications followed by cooler, wetter periods causing slow plant growth and increased drainage.

2.3.2 **Plant Uptake and Animal Utilisation**

Soil sulphate-S moves to plant roots mostly by mass flow (Nye and Tinker, 1977; Barber, 1984) and enters the plant in the root hair zone (process 3). Irrespective of whether S is the nutrient limiting pasture production, plant S uptake tends to increase with an increase in concentration of sulphate-S in soil solution (Goh and Gregg, 1982a; Rennenberg, 1984; Boswell and Swanney, 1988; Nguyen *et al.*, 1989a, 1989b; Saggar *et al.*, 1990a,b) indicating some passive uptake of sulphate-S by plants. Rennenberg (1984) indicated that plant root cells are not equipped to prevent an uptake of excess sulphate-S. However, most of the sulphate-S taken up in excess of the plant's requirement remains present as sulphate-S when the S supplies are greater than needed for amino acid formation (Cornforth *et al.*, 1983). Some of this excess sulphate-S may exchange back across root membranes into the soil, particularly in periods when transpiration is negligible.

Interactions of factors such as plant species, plant age, rooting depth, soil moisture content in the profile and potential evapotranspiration from the sward, produces differences in plant uptake observed by various authors. Gregg and Goh (1982) observed the differences in the ability of pasture species to take up S, where larger amounts of labelled gypsum placed at different soil depths were recovered from improved pasture compared to unimproved pasture.

The amount of S involved in recycling from above ground plant litter (process 11) depends on the amount of herbage utilised by the grazing animals (process 12) which depends on the stocking rate and stock management (King and Hutchinson, 1976). Pasture utilisation can be as high as 90% in well grazed pasture (Gillingham and During, 1973) while in less intensively managed systems, pasture utilisation by grazing animals can be as low as 50% (Lambert *et al.*, 1983). Pasture not utilised has the potential to become decomposing plant litter (process 11). Poor utilisation will apparently increase the fertiliser required to produce a given amount of animal products, provided pasture growth remains S responsive. This has been discussed with respect to P requirement by Conforth and Sinclair (1984). The significance of this effect depends upon the rate of loss of S from productive areas of pasture by transfer of animal excreta.

The animals use only a small proportion of the nutrients they ingest and 60 to 95% of the ingested nutrients are returned to pasture in the form of dung and urine (process 13) (Barrow and Lambourne, 1962). A large proportion (50 to 60%) of the S returned in animal excreta is in an immediately plant available form (process 14) (Till, 1975). However, faecal S that is not present as sulphate-S form is mineralised more slowly than plant S (Barrow, 1961). Dung patches may be sites of temporary S immobilisation (Phimsarn, 1991).

Haynes and Williams (1991) found that in sheep urine patches, elevated sulphate-S concentrations in the surface 2.5cm of soil persisted for about 40 days in summer but only 20 days for winter when significant leaching occur. Sulphate-S accumulated in the urine patch after urination may be immobilised by the microbial biomass into organic forms or taken up by plant growth. A range of 13 to 25% of urine S has been reported to have been immobilised during the first few months after application (Williams and Haynes, 1990). Rates of sulphate-S decline in urine patches are dependent upon the complex interactions between temperature, rainfall, plant and micro-organism growth.

On hill country pastures, significant quantities of nutrients are transported to flat areas of land where stock tend to camp from the steeper slopes where the stock graze (Gillingham and During, 1973; Saggar *et al.*, 1990a,b). Research has shown that 60% of dung and 55% of urine can be deposited in campsite areas which occupy only 15 to 31% of the total land area (Haynes and Williams, 1991). This varies with the percent area of each land slope category in a paddock (Rowarth, 1987). This effect of animal behaviour results in the S cycle being more efficient on completely flat areas than mixtures of flat and steep slopes.

2.3.3 **Immobilisation and Mineralisation**

There are two major pathways for transformation of sulphate-S to organic S; either by, i) direct microbial immobilisation (processes 1, 10, and 18) or, ii) by assimilation during protein synthesis in plants (process 3) and return of plant material and animal excreta as dung to soil (processes 11, 13, 15, and 16). Organic S can become available again for plant uptake via mineralisation (processes 2, 9, and 17). Understanding the immobilisation/mineralisation processes is central to the mechanisms involved in S retention in soils and provides more meaningful interpretation of the fate of applied S.

The immobilisation of sulphate-S to organic S via processes labelled 1 and 10 in Figure 2.3, involves more than one mechanistic pathway because more than one type of organic S compound will be formed by the process depending on the microbial need for sulphate-S. Similarly the concurrent mineralisation of organic S to sulphate-S via processes 9 and 2 consists of several mechanisms involving different selective and non-selective enzymes occurring simultaneously so that, it is difficult to separate out individual processes and rates. For example, the hydrolysis of ester sulphate-S is catalysed by sulphatase enzymes (Strickland and Fitzgerald, 1984; Fitzgerald and Strickland, 1987), of which arylsulphatase is only one of them and has been detected in a range of soils (Tabatabai and Bremner, 1970a,b; Cooper, 1972; Speir *et al.*, 1980). Ganeshamurthy and Nielsen (1990) observed that arylsulphatase produced by plant roots and that produced by microorganisms are different in nature.

Because it is impossible to separate the many processes that occur during immobilisation and mineralisation, McGill and Cole (1981) simplified the complex system in their conceptual approach which assumed that the two broad definitions of organic S into bond classes, C-bonded and ester sulphate-S, could be mineralised independently via seperate mechanisms. They hypothesised that mineralisation of ester sulphate-S is regulated by the biological requirement for S (*Biochemical mineralisation)* whereas C-bonded S mineralisation is more closely associated with the concomitant mineralisation of C and N for energy needs (*Biological mineralisation*) by which some sulphate-S is released as a by-product. This hypothesis was supported by the results of Maynard *et al.*, (1984) when they observed that under conditions of excess sulphate-S, more of the S is incorporated into ester sulphate-S form versus C-bonded. Conversely, when S was in short supply the transformation of sulphate-S to C-bonded was favoured. Haynes and Williams (1992) also found in their field study that although the amounts of organic S accumulated by annual applications of 188 and 376kg SSP/ha was the same, there was higher ester sulphate-S accumulated in the 376 treatment than in the 188 treatment. However, the model of McGill and Cole (1981) can be viewed as an oversimplification of the system because it predicts that the synthesis of enzymes which cleave sulphate-S esters (sulphatases) is a function of microbial demand for S which for some enzymes, for example arylsulphatase, the formation is repressed by elevated sulphate-S concentrations, but the mechanisms for the synthesis of other alkylsulphatases are induced in response to microbial C and energy requirements (Fitzgerald, 1976), thus complicating this conceptual approach.

2.3.3.1 *Immobilisation and Mineralisation as Simultaneous Processes*

A further complication in studying mineralisation and immobilisation processes is because these processes have been established to occur concurrently (Swift, 1983; McLaren *et al.*, 1985). Radioactive S (^{35}S) has been used by many workers as a means of tracing the flow of S within the soils from one fraction to another (Freney *et al.*, 1971; Bettany *et al.*, 1974; Goh and Tsuji, 1979; McLaren *et al.*, 1985; Strickland and Fitzgerald, 1985; Ghani *et al.*, 1988). These studies provided further evidence for these two processes to be simultaneous. For example, Ghani and co-workers (1988) observed net mineralisation throughout the time of their incubation experiment and at the same time, the level of incorporation of the added ^{35}S increased. This illustrates the co-occurrence of immobilisation and mineralisation processes where a substantial amount of ^{35}S was immobilised at the same time as ^{32}S was mineralised . Concurrent activity is expected since organism growth requires mineralisation of C and N in soil organic matter. S associated with this organic matter will be released and soil derived sulphate-S plus the added $^{35}SO_4^{2-}$ label will be used in microbial synthesis.

2.3.3.2 *A Quasi-Equilibrium*

It is generally accepted that in well developed pastures, a steady-state is reached where pasture production and fertility reach a plateau (Climax stage, Fig. 2.2). At this stage of development, the pathway for transforming sulphate-S to organic S, by assimilation of S during protein synthesis in plants (process 3) plus utilisation by animals (process 12) and return as plant material plus animal excreta (dung) to soil (processes 11, 13, 15, and 16), is proposed to be in equilibrium with the direct microbial immobilisation (processes 1, 10, and 18) and mineralisation processes (processes 2, 9, and 17).

Walker (1957) suggested that the equilibrium level of total S under the 'best New Zealand conditions' would be 0.12% (or 1200 mg S/kg) and that it would take at least

50 years to attain such a level. Nguyen and Rickard (1988) on the other hand reported some data showing soil organic S reaching an equilibrium plateau of 400 mg S/kg within 25 years of regular superphosphate application. The reason for the large discrepancy is that total S or total organic S cannot represent equilibrium levels of S in a steady-state system because not all of total S or total organic S are susceptible to microbial degradation.

2.3.3.3 *Factors Affecting the Immobilisation/Mineralisation Equilibrium*

Although many details of the immobilisation/mineralisation equilibrium are poorly understood, it is well established that the equilibrium is controlled by factors influencing the growth of micro-organisms such as moisture (Chaudry and Cornfield, 1967a), temperature (Chaudry and Cornfield, 1967b), pH (Williams, 1967; Swift, 1983; Hale and Fitzgerald, 1990), food (energy) supply (Barrow, 1960a,b,c) as influenced by soil depth (David *et al.*, 1983), presence and absence of plants (Freney and Spencer, 1960; Maynard *et al.*, 1985), organic matter addition (Saggar *et al.*, 1981b) and the amount of sulphate-S present (Maynard *et al.*, 1985). Similar factors have been shown to influence the level of sulphatase enzymes in soil (Tabatabai and Bremner, 1970; Speir, 1977; Lee and Speir, 1977).

Effect of removing sulphate-S

Periodic removal of sulphate-S by leaching in open incubation is considered to be analogous to plant uptake of S and has been used to characterise patterns of mineralisation. Tabatabai and Al-Khafaji (1980) observed that the release of sulphate-S in an open incubation system was linear with time over an incubation period of 26 weeks. In contrast, Maynard *et al.* (1983), Ellert and Bettany (1988), Ghani *et al.* (1991) showed curvilinear relationship between mineralised S and incubation time. Pirela and Tabatabai (1988) showed that the relationship between S mineralised and incubation time was linear for some soils, and curvilinear for others. The decrease in rate of mineralisation is explained by Ghani and co-workers as a result of the decrease in easily metabolisable C. In the presence of plants, the amount of S mineralised in soils increases (Freney and Spencer, 1960; Nicholson, 1970; Tsuji and Goh, 1979; Maynard *et al.*, 1985) as sulphate-S removal by plants stimulates mineralisation to counteract the effect of sulphate-S removal on the equilibrium. In addition, plant roots may sustain the supply of easily metabolisable carbon. Another explanation of the equilibrium favouring mineralisation, is due to the presence of plants increasing biological activity by increasing sulphatase enzymes produced by plant roots (Speir *et al.*, 1980).

Effects of adding C, N, and S.

The activity of the microbial population is affected by the availability of essential nutrients, particularly C, N, and S. To simulate the effect of the return of these nutrients in plant residues and animal excreta on the transformation of S in soils, several incubation studies have been conducted to measure the changes in immobilisation and mineralisation rates as affected by the addition of C (Stewart *et al.*, 1966), with or without N and/or S (eg., Saggar *et al.*, 1981b; McLaren *et al.*, 1985; Ghani *et al.*, 1992).

The addition of C will increase the C:S ratio in organic matter which should result in the equilibrium favouring immobilisation to offset the stress in the equilibrium brought about by the addition of C as more S will be needed by microorganisms to utilise the added C. Incubation experiments with added C have all shown to decrease rate of mineralisation as immobilisation becomes favourable as C-S organic gets formed..

The amount of net immobilisation is further increased when sulphate-S is added together with C. Saggar *et al.*, (1981b) found that the amount of added C that remained in the soil, was higher when no sulphate-S was added compared to the soils where C was added together with S. These workers suggested that added S led to increase microbial C and products thereof, whereas more C was lost through respiration with the small amounts of S that was turned over. Barrow (1969) found that when the C:S ratio in soils was below 200, sulphate-S was accumulated and was immobilised when the ratio was above 400. Stewart *et al.*, (1966), working with pure compounds, also found that when C was added as cellulose, more S was needed (C:S ratio of 300) for maximum decomposition compared to C added as glucose which required less S (C:S ratio 600-900) for decomposition. The less available C in cellulose compared to glucose means a higher S requirement for production of extracellular enzymes by microorganisms for cellulose decomposition. These results illustrate that the decomposition of added C is dependent on available soil S.

Saggar *et al.*, (1981b) found the microbial population increased when C was added as evident from increase in respiration rate or evolution of CO_2 from incubated soils. Ghani *et al.*, (1992) in a more comprehensive study found that the microbial population also increased when C was added as glucose and they also found that there was a further increase when C was added together with N and S. On the other hand, the addition of N and S without C showed no effect on microbial population.

In the field, the situation is complicated by the presence of plants. Sulphate-S removal by plant uptake increases mineralisation, but on the other hand plant residues will increase the C:S ratio of the soil which encourages immobilisation. The C:S ratio in plants is usually wider (>200) than in the decomposers eg., microorganisms (<50) (Barrow, 1960; Saggar *et al.*, 1981; Chapman, 1987a,b). The narrower C:S ratio in decomposers allow them to derive energy from plant material through respiring C and concurrently immobilises much of the plant S via their tissues.

2.4 SUMMARY AND CONCLUSIONS

The most obvious conclusion from the literature is that, although fractionation of organic S into ester-sulphates (HI-reducible) and C-bonded, have enabled the formulation of S transformations models (eg., McGill and Cole, 1981), it gives little if any information on the nature and size of the organic S fraction that is susceptible to enzymatic release. Several laboratory incubation studies (eg., Houghton and Rose, 1976; Fitzgerald *et al.*, 1984; McLaren *et al.*, 1985; Strickland and Fitzgerald, 1985; Ghani *et al.*, 1988) and in field plus laboratory studies (eg., Freney *et al.*, 1975; MacLaren and Swift, 1977; Goh and Tsuji, 1979; Goh and Gregg, 1982b) have shown that mineralised sulphate-S can be originated from both HI-reducible and C-bonded soil S fractions. Further studies to categorise the chemical nature of soil organic S appear to be unjustified.

It is also obvious from reviewing the literature that despite any method used to quantify the balance between immobilisation and mineralisation processes defining the ability of the soil to supply S, pasture requirement for that supply will always depend on the availability of other nutrients like P, N, and C. As N and C are added biologically, improving soil P status using P fertilisers appear to have the biggest impact on soil organic S. Thus, this study is focused on the interaction between S and P in increasing pasture productivity by promoting legume growth and biological fixation of N. The supply of C from the soil and the atmosphere is considered adequate for the assimilation of S, P, and N.

Therefore, while efforts to find a better index of S availability are still required, it is believed that such efforts may be wasted if they are not accompanied by efforts to also develop better models that take into account the availability of other nutrients. The traditional method of determining the pasture S requirement by regressions of RY as the pasture yield parameter against an index of soil S availability is questionable.

2.5 THE CONCEPT OF A MODEL

As most of this thesis is devoted to the development of models to predict pasture yield from soil S status, a discussion of the principles of modelling is needed to introduce the logic behind the approach taken.

Hillel (1977, p.14) mentioned, "The real world or indeed any perceivable system within it, is altogether too complex for our limited intellect to comprehend or to define in its entirety. In dealing with any problem, therefore, we are obliged to take the easy way out, which is to imagine the system to be simpler than it really is, by considering only aspects of it which pertain to the problem at hand." The concept that Hillel (1977) was alluding to is that of a *model* which he defined as, a simplified, and hence a more readily definable and more easily tractable, version of reality.

2.5.1 **Fundamental Principles of Modelling**

One of the most intriguing aspects of modelling, is that they help improve our knowledge as the models themselves evolve. From the best available evidence, mathematical equations are formulated to describe how we think the system behaves. By checking if the predictions we achieve fit experimental results, when circumstances change, we decide if the model is working or we revise and try again. In other words, the advancement of theory can only occur with experimentation. Models are only meant to compliment experimentation, not to take its place.

Obviously, the predictions from a model can never be exact, and the conclusions that are drawn from the uncertainties will bear further testing, research, re-research, as do our models. It is, therefore, not the intention of this study to develop a 'complete' model that will predict fertiliser requirements for all farming situations, rather to illustrate that modelling is an ongoing process that evolves with experience, as is reality. Hence, the more advanced the model is, the wider the set of circumstances it can be applied to. Figure 2.4 represents this ongoing process in model advancement.

People are often not regarded as part of a model. However, the bringing together of people from many disciplines, like scientists, technologists, mathematicians, farmers, and economists, will naturally provide greater resource and experience. It also reflects how ideal farm management practices should be chosen, by taking into account as many aspects of farming as possible, which impacts on the availability of nutrients. From a soil scientists point of view, simplicity is the key to start communication and is the emphasis of the models developed in this thesis.

The very beginning of model development therefore, starts with *Word models* and *Conceptual models*. In order that the problem be precisely defined and so that all involved can agree on the goals and objectives and on the essential elements of the model, verbal communication (to hypothesise) and formulation of concepts is perhaps the most basic but an integral part of the modelling exercise.

From a conceptual model, experiments are designed and conducted. By observing the results, mathematical models are then formulated to describe how the system is thought to behave. The models are then validated by comparing model result with real-system data either by comparison with historical records or forecasting of future events. If the model measures and predicts the variables of interest with sufficient accuracy, it will then open up new concepts, hypotheses and problems so that the model evolves, as in real natural systems, otherwise, we try again by improving current concepts, experiments, and mathematical models. The point emphasised is that the success of a model should be measured by how it opens up new opportunities for expansion and not just by exhibiting an ‘excellent fit’ with the real system.

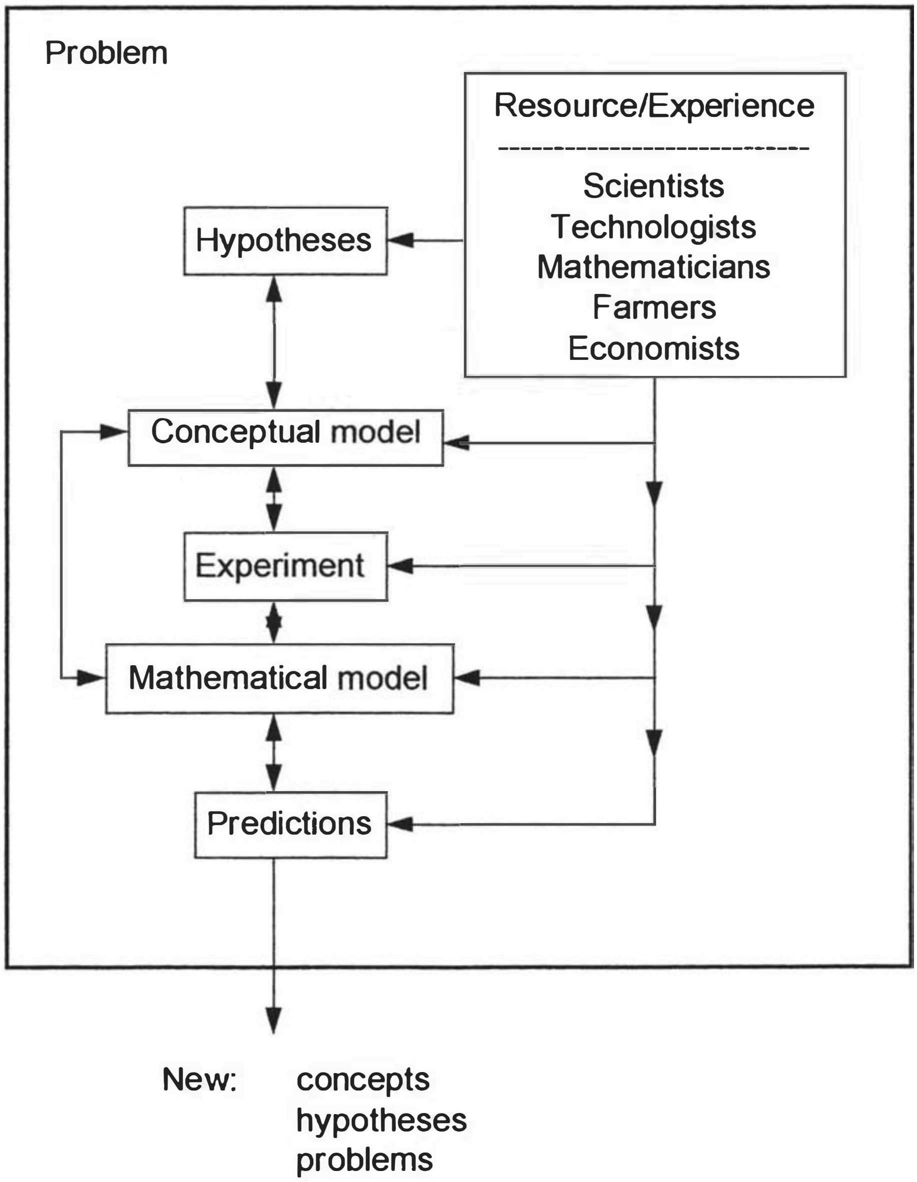

Figure 2.4 The process of model development.

2.5.2 Types of Models

Following are several definitions of types of models which are not necessarily mutually exclusive.

An *empirical model* describes a system, without necessarily demonstrating an understanding of that system. Mathematical equations are fitted to data sets by regression analysis, so that a given variable can be estimated from one or more other variables. The calibration of soil test values to crop yield are clearly an example of this empirical modelling approach. According to Hillel (1977, Pp.16), the formulation of an empirical model is perhaps the earliest and most primitive stage in the development of any science. Chapters Four and Five describe models of this nature.

Mechanistic models are statements as to how particular processes occur in terms of the underlying mechanisms. They provide descriptions with understanding. The Ministry of Agriculture and Fisheries (MAF) Soil Fertility Services (SFS) S model (Sinclair and Saunders, 1984) is an example of a mechanistic model.

Dynamic models include time as a variable (in contrast to *static models*). Most models derived in recent times to predict S leaching losses in New Zealand pasture systems are dynamic in nature, for example, the models developed by Heng (1991), and Sakadevan (1991). These two models used a soil water balance to follow the movements of S in the soil profile to predict S leaching losses. Because dynamic models can take into account factors that may vary with time, they are appropriate in modelling soil-plant systems.

Deterministic vs *stochastic* models: While a deterministic model predicts values as uniquely definable outcomes, a stochastic model predicts values without certainty and have probability functions associated with them.

The models presented in this thesis will encompass several of these types of models in conjunction. It is emphasised that simplicity is the key to start communication between disciplines and is the emphasis of the models developed in this thesis.

CHAPTER THREE

PASTURE YIELDS AT FIELD TRIALS UNDER SIMILAR CLIMATE AND SOIL TYPE, BUT VARIABLE SOIL FERTILITY

3.1 INTRODUCTION

Models cannot be developed or validated without extensive data sets. The data sets that would be required for developing and validating models to predict pasture yields and estimate pasture S requirements are; i) total herbage and legume yields (with and/or without applications of S, P, and N fertilisers) and ii) indicators for the soil supply of S, P, and N nutrients.

In this chapter, field experiments to collect pasture yield data under similar climate and soil type, are discussed. The soil samples collected from the field trial sites at the beginning of the experiments, are used in Chapter Four to examine the abilities of the soils to supply S, by adopting chemical extraction techniques as a means of soil testing. The Olsen P soil test is considered an adequate indicator of the soil's ability to supply P. It is considered that these data sets will be the minimum required to develop models that will improve our understanding of the roles that S and P availabilities play in regulating available* N.

As mentioned in the previous chapter, researchers develop models by simplifying a system, and considering only those aspects of the system which pertain to the problem at hand. The aspect of legume\grass swards, that is at the core of the problem here, is that the *primary* nutrient influencing pasture production is N (Ball and Field, 1987). This aspect has to be incorporated into the concepts from which any model to predict pasture yields is developed, else, that model will be too gross a departure from reality.

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* For definitions of the words 'availability' and 'available', see Chapter One, p.5

The logic behind the models to be developed from the yield data reported in this chapter, is that soil S and P availabilities affect total herbage yields by limiting legume growth, hence the amounts of N fixed, which imposes an upper limit on the amounts of available N susceptible to absorption by plant roots.

3.2 METHODOLOGY

3.2.1 **1990/1992-Ballantrae Field Trials**

The trial sites for these field experiments were selected to represent a wide range in soil fertility. The fertility range is due to different fertiliser histories, and differences imposed by animal grazing behaviour and excretion pattern as affected by topography, aspect, and slope category. All site locations had similar soil types and climatological data, that is, daily rainfall, daily hours of sunshine, and daily temperatures. Therefore, the differences in pasture yield can be assumed to be directly related to differences in soil fertility only, with the differences caused by soil type and climate having been eliminated.

3.2.1.1 ***Location***

The trials were located at the Hill Country Research Station at Ballantrae, which is situated 20km north east of Palmerston North in the foothills of the Southern Ruahine Ranges. Soils are Yellow-grey earths, Yellow-brown earths (New Zealand classification) and related intergrades developed from tertiary sediments. They receive an average annual rainfall of 1000-1400mm. These trials will be referred to as '1990/1992-Ballantrae' from here on to distinguish them from another series of trials established in 1993, used in Chapter Six.

3.2.1.2 *Fertiliser History*

Trial sites using exclusion cages (0.5m^2) were established on four 10ha farmlets. Each farmlet had a different fertiliser history (Table 3.1). From 1975 to 1980, a pair of farmlets had low fertiliser (LF) input (125kg SSP/ha/yr), and a pair had high fertiliser (HF) input (576kg SSP/ha/yr).

Since 1980, annual topdressing of 125kg SSP/ha (LFLF) was continued on one of the LF farmlets while on the other, topdressing had ceased (LFNF). Similarly, on the HF farmlets, topdressing was terminated after 1980 on one of the pair (HFNF) while on the other, topdressing was continued at a rate of 375kg SSP/ha (HFHF).

On each of the four farmlets, two slope categories, 0-12° corresponding to low (L) slopes, and 13-25° corresponding to medium (M) slopes were chosen as separate sites to represent the difference in soil fertility due to topography and stock behaviour (Saggar *et al.*, 1990a, 1990b). This gave a total of eight sites for this series of trials (Table 3.1). Previous studies (Lambert *et al.*, 1983; Saggar *et al.*, 1990a) on these farmlets have indicated that these slope categories would allow the effect of micro-topography on herbage accumulation and total soil P to be assessed adequately. These studies have described in detail, the increase in soil S, P, and N nutrient content and the influence on soil S and P fertility indices, caused by uneven dung and urine return. In general, nutrient accumulation can be expected to occur on low slopes and track areas, except where the prevailing wind has a major influence. For example, the LFNFM site accumulates more excreta because of its sheltered position.

Table 3.1 Some chemical characteristics of the topsoil (0-75mm) and fertiliser history of Ballantrae trials

Trial Site	pH	Total N (mg/kg)	Total S (mg/kg)	Total P (mg/kg)	Phosphate extractable S (mg/kg)	Olsen P (mg/kg)	Fertiliser History
LFNFL	5.18	5119	1109	813	9.7	14.4	1975-1980: 125kg SSP/ha/yr Since 1980: NIL
LFNFM	5.14	5241	1053	750	8.0	16.8	1975-1980: 125kg SSP/ha/yr Since 1980: NIL
LFLFL	5.26	5017	1131	645	13.2	21.1	1975-1980: 125kg SSP/ha/yr Since 1980: 125kg SSP/ha/yr
LFLFM	5.26	4828	1017	643	15.0	16.0	1975-1980: 125kg SSP/ha/yr Since 1980: 125kg SSP/ha/yr
HFNFL	5.42	5226	971	790	11.2	26.7	1975-1980: 576kg SSP/ha/yr Since 1980: NIL
HFNFM	5.49	4042	781	561	8.3	17.0	1975-1980: 576kg SSP/ha/yr Since 1980: NIL
HFHFL	5.36	5312	745	917	35.3	39.2	1975-1980: 576kg SSP/ha/yr Since 1980: 375kg SSP/ha/yr
HFHFM	5.52	4721	834	779	31.5	31.5	1975-1980: 576kg SSP/ha/yr Since 1980: 375kg SSP/ha/yr

3.2.1.3 *Combinations of S, P, and N Fertiliser Treatments*

Twelve plots (2.3 x 1.2m) consisting of three replicates of each treatment were laid out on each site to provide four treatments (Table 3.2), consisting of a control (CONTROL); S alone (+S); S together with P (+SP); and S together with P and N (+SPN). To complete all the possible combinations of S, P, and N, twelve extra plots were added to the LFLFM and HFHFM sites consisting of four additional treatments in three replicates (Table 3.2). A study of all possible combinations of S, P and N was not conducted on all sites due to cost and time constraints. The medium slope sites were selected however, because they were expected to represent the major area of grazed landscape at this location, within North Island hill country. In addition, nutrient loss by animal transfer suggested that they would be responsive to maintenance applications of fertiliser.

3.2.1.4 *Soil Sampling and Fertiliser Application*

Eight topsoil core samples (0-75mm) were collected from each plot at the start of the experiment prior to fertiliser application. Representative samples of the 75-150mm and 150-300mm soil depths were also collected from each of the replicate plots at each site.

Table 3.2 summarises the fertiliser treatments and dates of applications at Ballantrae. The first topdressing of the experimental sites was in autumn, April 22 1990, (A) at the rate of 50kg ha^{-1} for all nutrients; S as gypsum, N as urea, and P as monocalcium phosphate (MCP). A second application of S and N at the same rate was applied in spring on October 13 1990 (O). Re-topdressing of all nutrients on June 15 1991 (J) provided the final application. The topdressing regimes for S, P, N, and the micronutrient, Mo, were designed to remove any constraints that the availability of these nutrients may place on pasture growth. The trial sites were covered with plastic sheets during annual fertiliser application to the farmlets.

Table 3.2. Summary of treatments applied to Ballantrae trials.

Treatment Code	Timing and Application Rates of fertilisers*		
	Gypsum (50kgS/ha)	**MCP** (50kgP/ha)	**Urea** (50kgN/ha)
CONTROL	-	-	-
+S	AOJ	-	-
+SP	AOJ	AJ	-
+SPN	AOJ	AJ	AOJ
Extra treatments for LFLF<u>M</u> and HFHF<u>M</u> sites only:			
+N	-	-	AOJ
+P	-	AJ	-
+SN	AOJ	-	AOJ
+PN	-	AJ	AOJ

* **One basal spray-application of molybdenum as hydrated Sodium Molybdate ($Na_2MoO_4.5H_2O$) at a rate of 175g/ha during A.**

A	April 1990	O	October 1990	J	June 1991

3.2.1.5 *Pasture Yield Measurements*

An exclusion cage ($0.5m^2$) was located on each plot. The cage and plot sizes were chosen so that a cage could be placed in three different positions within each plot. During each harvesting period, the cage is placed in one of these three positions, while the rest of the plot was left to be grazed by sheep. Pasture production was assessed by harvesting the area under the frame exclosures at each plot. The herbage was cut 5-10mm above ground level with handshears during each harvest. The cages were then moved to the next pre-trimmed (5 -10mm above ground level) area in the plot in a rotational manner.

Harvests were carried out at 6 - 12 week intervals depending on the rate of growth, and were taken after approximately 120mm of pasture growth. The experiment was conducted over two consecutive years (April 1990 to May 1992) during which, there were thirteen harvesting events.

After recording the fresh weight of clippings from each plot, the clippings were thoroughly mixed and two sub-samples of 50g were taken for dry matter assessment and botanical analysis. One sub-sample was oven dried at 60°C for 24hr. Dry matter percentages were calculated and yields converted to total dry matter production per hectare. The second sub-sample of the fresh clippings from each plot was taken for assessment of botanical composition. Herbage was separated into grass and legume components, dried, then weighed to obtain the botanical composition of these two components. The total dry matter production per hectare was then multiplied by the percentage legume composition to obtain the legume dry matter production per hectare.

3.2.1.6 *Statistical Analysis*

Pasture yields from the replicated treatments for each harvest at each site were subjected to statistical analysis using a General Linear Model Procedure (Spector *et al.*, 1985).

3.2.2 **Acetylene Reduction Assay**

The method is a modification of the acetylene reduction assay used by Hardy *et al.*(1968). Details of the modifications are described by Hoglund and Brock (1978). The soil cores for the estimates were taken on the same day as the fourth harvesting event, November 16 1990. Seven soil core samples from each plot were placed in a

580ml jar. After sealing, 30ml of the air head space was replaced by acetylene gas and the jars incubated for 60 minutes in a shaded area. A gas blank not containing any soil cores was also incubated. At the end of the incubation, gas samples were transferred to evacuated vials using double ended needles. Gas samples were analysed for ethylene by gas chromatography. Time and area factors were then used to estimate the amounts of N fixed in kg N/ha/day. It is assumed that 1 mole of $CH \equiv CH$ reduced to $CH_2 = CH_2$ is equivalent to 1/3 mole $N \equiv N$ being reduced to NH_3. The amounts of N fixed per day was assumed to be the same for all days during the period from 25 August 1990 to 12 December 1990 (111 days). The amounts of kg N fixed per day on 16 November 1990 were then multiplied by the number of days as an estimate for the amounts of N fixed during spring 1990.

3.3 RESULTS

3.3.1 Control Plot Yields: Effects of Soil Fertility as Influenced by previous Fertiliser Histories and Stock Camping Behaviour

At each site, the mean harvested yield from the unfertilised control plots is mostly a function of the soil fertility built up from previous fertiliser applications and the deposition of grazing animal excreta.

The accumulated pasture production on the unfertilised control plots over the two year period (April 1990 to May 1992), are presented in Figure 3.1. The yields varied from 14678 kg DM/ha on the LFNFL site to 39235 kg DM/ha on the HFHFL site. The magnitudes of these biennial yields, are consistent with annual yields measured by previous workers at similar sites on these farmlets (Lambert *et al.*, 1983; Mackay *et al.*, 1988; Sakadevan, 1991). Larger yields are associated with greater fertiliser inputs and greater excreta return on the low slope areas at the HF farmlets. The effect of the prevailing wind at the LF farmlets results in the animals spending more time and hence, more excreta returns on the protected east-faced medium slopes. This effect was more pronounced at the LFNF farmlet than the LFLF farmlet where the LFLFM site was not as far away from the LFLFL site compared to the position of the LFNFM site relative to the LFNFL site.

The most striking influence of the HF regimes on pasture growth was the more rapid pasture growth rates that occurred in the autumn-winter period of each year. This growth pattern is consistent with the more botanically detailed sward growth patterns observed by Lambert *et al.* (1983).

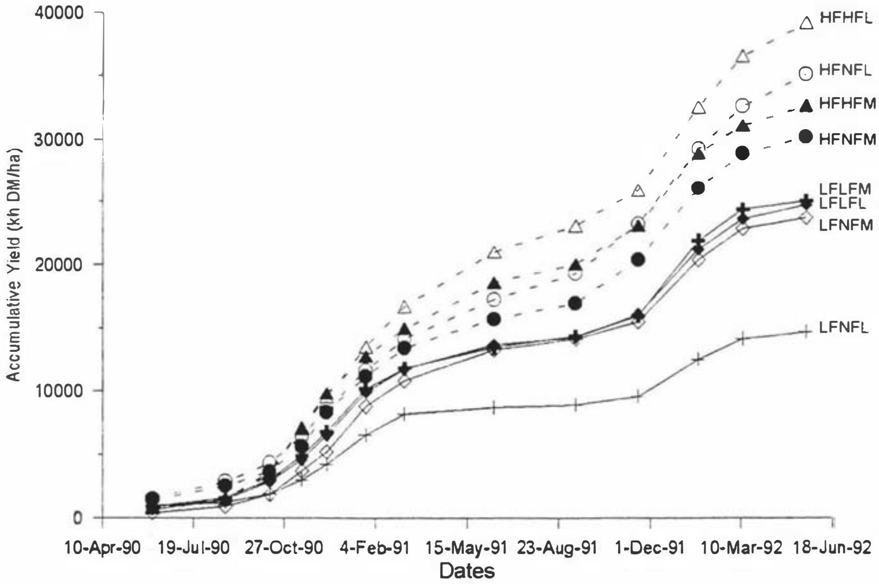


Figure 3.1 Accumulated yields over two years (autumn 1990-autumn 1992) on the control plots for all sites at Ballantrae.

When the yields were separated into annual accumulated yields, the values ranged from an average 9893 kg DM/ha at the LF farmlets to an average 20089 kg DM/ha at the HF farmlets, averaged across the two slope categories (Fig. 3.2). Year 1 data consists of the accumulated harvested yields from the first to the seventh harvesting event

(Autumn 1990 to Autumn 1991), while Year 2 data consists of the accumulated harvested yields from the eighth to thirteenth harvesting event (Autumn 1991 to Autumn 1992). The histogram (Fig. 3.2) shows the effects on pasture production of the decrease in soil fertility over ten (Year 1) and eleven (Year 2) years since 1980, when annual applications of SSP fertiliser were terminated.

In the LF farmlets where annual topdressing of 125kg SSP/ha/y either ceased (LFNF farmlet) or continued (LFLF farmlet), pasture yields showed a decrease of 13% during Year 1, and 31% during Year 2. In the HF farmlets where the annual topdressing of 576 kg SSP/ha/y either ceased (HFNF farmlet) or continued at a rate of 375 SSP/ha/y (HFHF farmlet) since 1980, the decrease in fertility at the HFNF farmlet resulted in a 15% decrease in pasture yield of during Year 1 and 6% decrease during Year 2. Five years earlier, from Spring 1986 to Spring 1987, the corresponding values for the LF and HF farmlets were 16% and 10% respectively (Mackay *et al.*, 1988).

These differences between annual pasture yields on the sites located in the farmlets that continued to receive SSP applications compared to those that did not, may be considered as a measure of the residual values of previously applied fertiliser. If so, then the residual value of SSP seems to be reducing faster at the LFNF farmlet compared to the HFNF farmlet. This applies except for Year 1 where the pasture yield reduction on the LFNF farmlet was 13% compared to 15% on the HFNF farmlet. The size of the yield differences between continued and discontinued SSP treatments varies amongst years and does not follow a simple increasing trend as years after cessation of SSP application increase. Such variations are likely due to the annual differences of climate affecting plant nutrient demand and availabilities. This concept will be incorporated into the dynamic models presented in Chapter Seven where variations in pasture growth as affected by climate and S and P availabilities in soil, will be investigated.

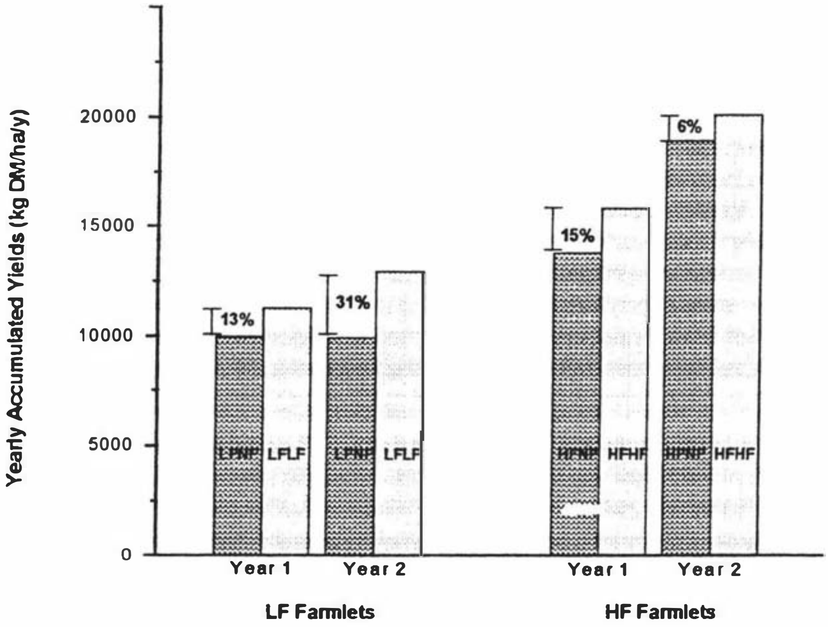


Figure 3.2 Annual accumulated yields for Year 1 (Autumn 1990 to Autumn 1991) and Year 2 (Autumn 1991 to Autumn 1992) at Ballantrae.

3.3.1.1 *Control Plot Yields Relative to Total S, P, and N in Soils*

Perhaps the most logical approach to estimating the ability of a soil to supply nutrients, is to measure the total amount of nutrients it contains. However, it has long been established that the total amount of nutrients in soils are not always proportional to the amounts that are available for absorption by plant roots. Nevertheless, these relationships were considered worth investigating, to illustrate the process involved in building up models. The emphasis is to observe patterns in the relationships between pasture yields and indices of soil fertility, so that hypotheses and concepts can be made from which mathematical models are formulated. Such models explain how we think the system behaves and enable the design of experiments that clarify and test our assumptions (Fig. 2.4).

As shown in Table 3.1, the cóntinued annual applications of SSP fertiliser on the LFLF and HFHF farmlets did not result in higher total S, P, or N accumulated in the soils of the selected trial sites. While there was no clear pattern concerning total P and total N, the contrary was observed with total S. It was observed that the amounts of total S were generally lower in the soils sampled from the HF sites than those sampled from the LF sites, despite the higher amounts of S that had been applied as fertiliser. Sakadevan (1991) reported similar total S and total N values from similar sites, at Ballantrae. In his data, some sites located on the LF farmlets did accumulate more S than some sites located on the HF farmlets, but the pattern was not observed in all cases, as in this study. These differences in soil nutrient content, are likely to be due to the spatial variability of nutrient accumulation under urine and dung patches in hill country farms.

Figures 3.3, 3.4, and 3.5 show the relationship in the control plots between annual accumulated pasture yield and soil total S, total P, and total N respectively, in soil samples taken at the beginning of Year 1 (April 1990). Soil total S increased while accumulated yield showed a general decline. This trend was not observed in the relationship between soil total P and total N, and pasture yield.

Without closer examination of the relationships in Figures 3.3 - 3.5, it appears that a negative relationship exists between yield and soil total S, which indicates that soil total S may have potential as a predictor of pasture yield, but not soil total P or total N. Saggar *et al.* (1990) has already indicated that these farmlets are S leaky and proposed leaching as the major source of S losses. The lysimeter studies of Sakadevan (1991), showed that S mineralisation rates were higher at the HF sites than at the LF site selected for his study. It was also shown in his laboratory incubation studies, that HF sites contained more mineralisable S in the soil than soil from the LF sites. These results seems to indicate that the build up of labile organic S and higher mineralisation rates at the HF farmlets, are likely to result in higher amounts of soluble S susceptible to leaching throughout the year. Therefore, it is possible that due to these faster mineralisation rates, the leached soluble S amounts are replenished faster at the HF farmlets from organic S, causing lower soil total S despite the historically higher amounts of S applied as fertiliser to the HF sites.

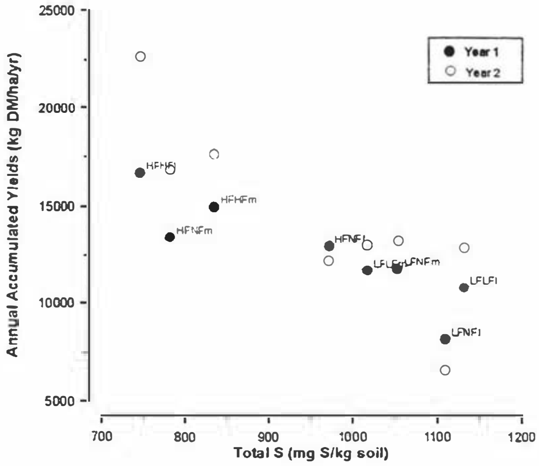


Figure 3.3 Relationship between annual accumulated pasture yields at the control plots and soil total S.

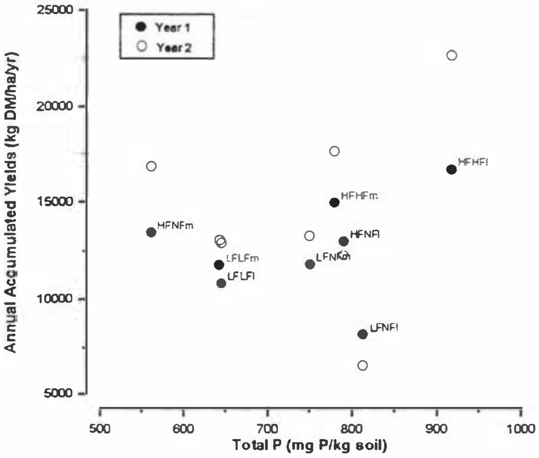


Figure 3.4 Relationship between annual accumulated pasture yields at the control plots and soil total P.

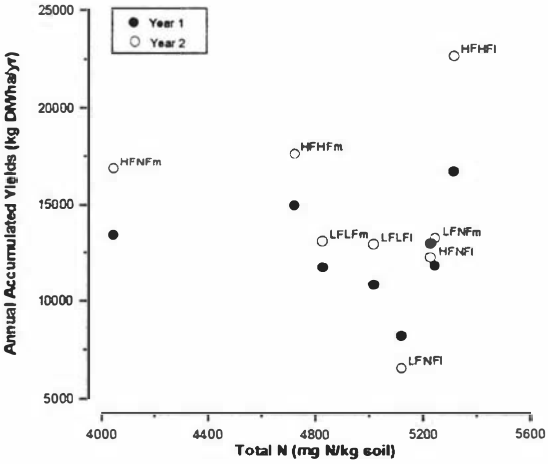


Figure 3.5 Relationship between annual accumulated pasture yields at the control plots and soil total N.

Increasing pasture yield with decreasing organic S seems to be illogical. However, it is proposed that the higher yields at the trials located at the HF farmlets may be associated with a faster rate of S cycling and higher amounts of sulphate and mineralisable organic S, rather than being related to the absolute amount of total soil S. The data of Sakadevan (1991), indicate that low soil total S is not necessarily associated with higher mineralisation rates and higher mineralisable organic S. Therefore, neither soil total S, total P, or total N can be considered as robust indicators of pasture yield.

3.3.2 **Pasture Yields as Affected by Different Combinations of S, P, and N Fertiliser Treatments**

Figure 3.6 depicts the results as histograms of annual pasture yields from all the fertilised and unfertilised plots. The same results are presented in Table 3.3 showing the biennial accumulated pasture yields.

3.3.2.1 *S Alone (+S treatment)*

Generally over the two years, there were only small increases in accumulated dry matter production resulting from S fertiliser addition (+S), except for the LFNFM and the HFNFM sites (Table 3.3). However, none of these increases were significantly different from the control yields, at the 90% level of confidence. These results indicate that at Ballantrae, S is not a key growth limiting nutrient and that there is generally an adequate soil supply of S at all sites due to previous SSP applications, which have enabled the accumulation of mineralisable soil organic S. Such accumulation was expected at most sites, but it was surprising that the sites located at the LFNF farmlets also did not respond to applied S. This was despite the cessation of 125 kg SSP/ha/yr applications ten years earlier.

Similarly, when the harvests were separated into seasons (Table 3.6), application of S alone did not produce significant yield increases during any season at any site. Mackay *et al.* (1988) reported an autumn response to S alone at a LFNF site during 1987, and winter responses at both a LFNF and a LFLF sites during the same year. The lack of response three years later, suggests that the availability of nutrients, hence pasture growth, cannot be a function of the S status of the soils only, but i) soil moisture and soil temperature may play very important roles in controlling microbial activity, hence differences in S availability among years, and ii) the utilisation of S fertiliser is likely to be affected by the availability of other nutrients like P. Therefore, the extent of pasture responses to S fertilisers, like N responses (Luo *et al.*, 1994) are likely to vary following different sequences of climate.

3.3.2.2 ***Sulphur Applied Together with Phosphorus (+SP treatment)***

Three out of the four LF sites showed significant growth responses to applications of S and P together (+SP) (Table 3.3). In contrast, all four HF sites did not show any significant growth response to the same treatment. The results of the +S treatment established that these sites either have an adequate soil supply of S, or other factors impose greater constraints on pasture growth than the availability of S. It is therefore more likely that, the growth response observed at the LF sites was a response to P rather than S in the +SP treatment. This was further supported by the observed significant differences in pasture growth on the +P plots at the LFLFM and the HFHFM sites where P alone was applied.

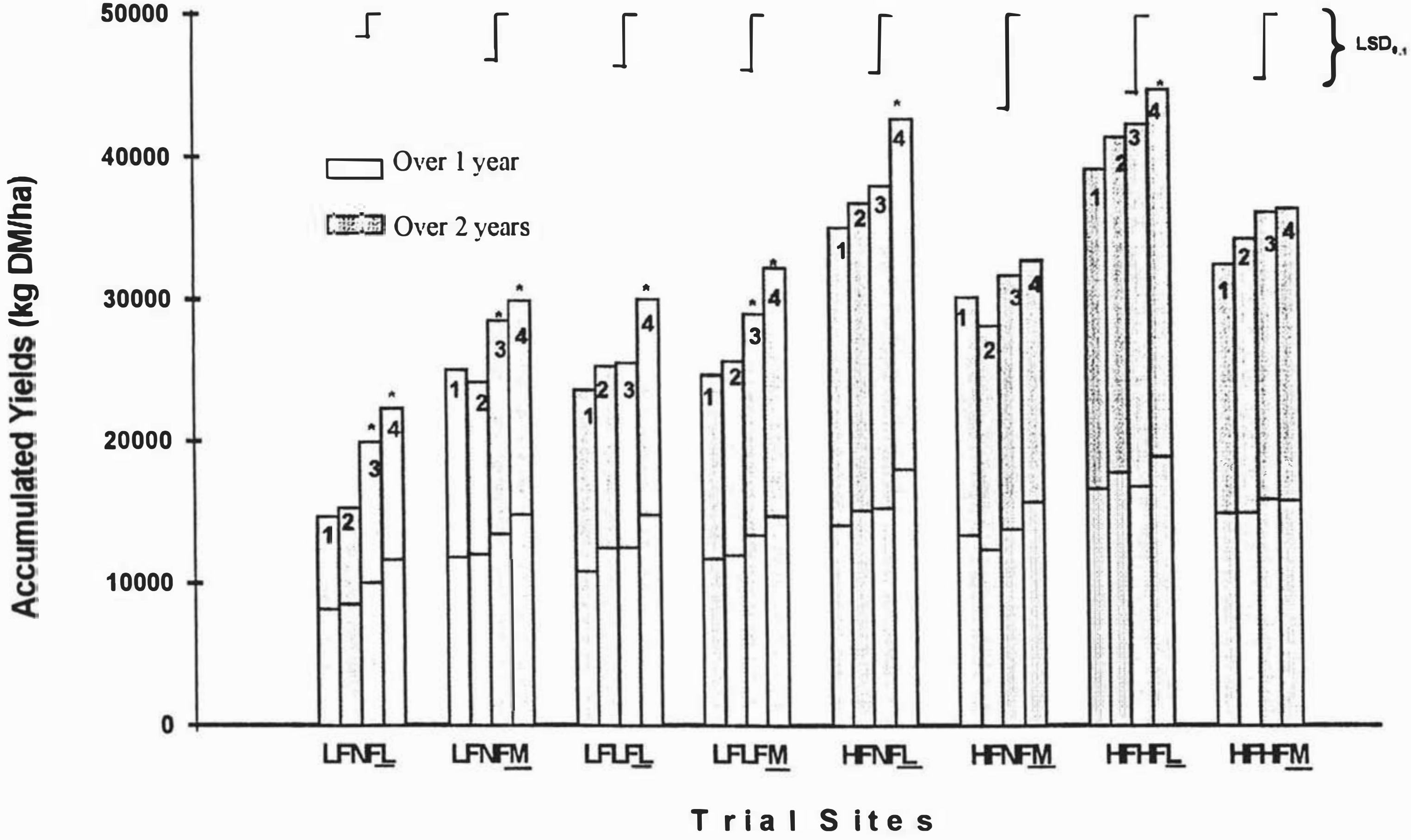
Short-term growth responses to S and P fertilisers result from alleviation of S and P deficiencies relating to protein synthesis and cell metabolism in pasture plants. On the other hand, long term pasture responses to S and P are mainly due to the associated increase in biological N_2 fixation as S and P promote legume growth (Palmer and Iverson, 1983; Mackay *et al.*, 1988; Wang *et al.*, 1989). The N fixed by short-term increases in legume vigour becomes available for grass growth after senescence, when legume tops and roots decompose, or after grazing, when ingested organic material is returned as excreta. Only the LFLFL and the HFNFL sites showed no significant differences in accumulated legume production over the two years (Table 3.4), suggesting that long-term soil S and/or P supplies at these two sites were adequate.

3.3.2.3 ***Sulphur Applied Together with Phosphorus and Nitrogen (+SPN treatment)***

Except for the HFNFM and HFHFM sites, all sites showed significant differences in biennial accumulated yields (Table 3.3) on the +SPN fertilised plots above the control. On the other hand, when N was applied alone (+N), to the LFLFM and the HFHFM sites only, the LFLFM site did not respond, while the HFHFM site showed a significant increase in biennial accumulated yield. This seems to indicate that in order to utilise applied N, adequate soil S and P supplies are required.

However, previous research has shown that N fertilisation dramatically reduces N_2 fixation and that, in the absence of N fertiliser, the majority of N assimilated by the grass tops is from indigenous soil N, while legumes obtain most of their N by fixation (Crush *et al.*, 1982; Ledgard and Saunders, 1982; Mundy, 1987; Ledgard, 1989). These studies showed that when N fertiliser was applied at a rate of about 100kg N/ha to mixed swards, much smaller proportions of N in clover were derived from fixed N as clover readily substituted fixed N for [the uptake of] fertiliser N. The studies by Ball *et al.* (1979) and Ledgard and Brier (1987) also showed that N_2 fixation is dramatically reduced when soil inorganic N is high under urine patches.

Hence, while on one hand, there is an increased demand by plants for S and P when N is applied, presumably to accompany the processes of protein synthesis and cell metabolism (Caradus, 1991), on the other, S and P requirements for legume growth are very much reduced under the same conditions. Therefore, assessment of the legume component of the swards as affected by the different S, P and N fertiliser treatments, will be of vital importance.



Key for treatments: **1 = Control, 2 = +S, 3 = +SP, 4 = +SPN**

Figure 3.6 Pasture yields accumulated over two years as affected by fertiliser treatments

Table 3.3 Biennial accumulated Pasture Yields (kg DM/ha) at Ballantrae trials as affected by fertiliser treatments.

Site	**Cont**	**+S**	**+N**	**+P**	**+SP**	**+SN**	**+PN**	**+SPN**	**LSD$_{\alpha=0.1}$**
LFNFL	14678$_{c}$	15346$_{c}$	-	-	19968$_{b}$	-	-	22356$_{a}$	1543
LFNFM	25048$_{b}$	24231$_{b}$	-	-	28541$_{a}$	-	-	29970$_{a}$	3188
LFLFL	23662$_{b}$	25313$_{b}$	-	-	25565b	-	-	30091$_{a}$	3621
LFLFM	24707$_{c}$	25667$_{cb}$	27092$_{cb}$	31018$_{a}$	29052$_{ba}$	29169$_{ba}$	32901$_{a}$	32328$_{a}$	3874
HFNFL	35178$_{a}$	36860$_{a}$	-	-	38102a	-	-	42819$_{b}$	3962
HFNFM	30241$_{a}$	28205$_{a}$	-	-	31765$_{a}$	-	-	32866$_{a}$	6533
HFHFL	39235$_{b}$	41509ba	-	-	42516ba	-	-	44872$_{a}$	5357
HFHFM	32586$_{d}$	34406$_{dc}$	37862$_{cb}$	38356$_{cb}$	36286$_{dcb}$	39789$_{ba}$	43444$_{a}$	36502$_{dcb}$	4450

abcd = T Grouping ($\alpha = 0.1$)

3.3.3 The Legume Component

None of the eight trial sites showed any significant difference in biennial legume yields when S was applied alone (+S) (Table 3.4). In contrast, application of S together with P (+SP), resulted in significant increases in accumulated legume yields at nearly all the sites, except LFLFL and HFNFL. Mackay *et al.* (1988) reported similar results at Ballantrae, and suggested that legume growth was limited primarily by P. These researchers concluded that, S became a factor limiting further increases in legume growth only after P deficiency was alleviated.

When the amounts of S and P accumulated in the topsoil (0-75mm) of the HF farmlets were compared with the amounts accumulated in the LF farmlets (averaging all slope units), Lambert *et al.* (1988) found that only 14% of the extra S and 47% of the extra P applied to the HF farmlets, above the amounts applied to the LF farmlets, could be accounted for. The results led these researchers to suggest that, "....in a circumstance of "submaintenance" superphosphate application (eg. the LFNF and HFNF farmlets), or where an alternative phosphatic fertiliser with lower S content is used, S deficiency may be a major limiting factor in terms of legume growth, and utilisation of soil and fertiliser P" (Lambert *et al.*, 1988, pp 100). The lack of response to the +S treatment at the LFNF and HFNF sites in this study however, does not support this view. Rather, in terms of S required to utilise P, it is believed that the HF farmlets with higher soil P levels are more likely to be S deficient because more S would be required to utilise the higher levels of P. This is supported by the results showing that on the two sites where P alone (+P) was applied, there was a significant difference in the legume yields over the control at the LFLFM site, while the HFHFM site showed no significant difference.

Table 3.4. Biennial accumulated Legume Yields (kg DM/ha) at Ballantrae trials as affected by fertiliser treatments.

Site	**Cont**	**+S**	**+N**	**+P**	**+SP**	**+SN**	**+PN**	**+SPN**	**LSD$_{\alpha = 0.1}$**
LFNFL	1235_c	1396_c	-	-	4439_a	-	-	3105_b	897
LFNFM	1544_b	1721_b	-	-	3973_a	-	-	3337_a	1243
LFLFL	2159_b	2736_{ba}	-	-	3720_{ba}	-	-	4803_a	2199
LFLFM	2100_{de}	1606_e	1831_{de}	4161_a	4467_a	1613_e	3305_{bc}	2771_{dc}	1080
HFNFL	3069_a	2310_a	-	-	2828_a	-	-	2287_a	n.s.
HFNFM	1872_b	2165_b	-	-	3833_a	-	-	2877_{ba}	1468
HFHFL	3205_{ba}	3147_{ba}	-	-	4928_a	-	-	1842_b	2308
HFHFM	2319_b	2119_b	1464_b	2164_b	4026_a	1353_b	1803_b	1768_b	1073

abcdc = T Grouping ($\alpha = 0.1$)

The efficiency of the +SP treatment at promoting legume growth was less affected by the application of N on top of S and P (+SPN) at the LF farmlets (Table 3.4). In contrast, at the HF sites, application of N fertiliser dramatically reduced the effects of the applied S and P on legume growth to levels that were not significantly different from the controls. This indicates that, N_2 fixation is still the dominant source of N in the LF sites, while at the HF sites, there is adequate soil inorganic N that legumes can readily substitute for fixed N (Allos and Bartholomew, 1959). In tandem with the higher levels of available N inhibiting the need for the sward to fix N at the HF farmlets, the grass associates would have also suppressed legume growth by shading.

3.3.3.1 ***Amounts of N Fixed by Legumes***

The ability of legumes to fix atmospheric dinitrogen (N_2) and the eventual transfer of fixed N to promote grass growth, makes applications of S and P fertilisers to stimulate legume growth the most significant aspect of fertiliser management in grazed pastures. Indications are that some 300 to 600kg fertiliser N/ha/yr would be needed on pure grass swards to sustain the level of forage production currently attainable from well managed grass-clover associations, sustained by an annual input of 150 to 300kg fixed N/ha (Hoglund and Brock., 1979; Field and Ball, 1982).

To investigate the amounts of N fixed by legumes, acetylene reduction measurements were conducted at the LFLFM and the HFHFM sites, where the four extra treatments were applied to include all possible combinations of S, P, and N.

The results show the amounts of N fixed were generally higher at the LFLFM site (0.3 - 1.0kg N/ha/day) compared to the HFHFM site (0.1 - 0.6kg N/ha/day) (Table 3.5). One reason for the observed results is that at the HF farmlets, the dominant grass associates suppress legume growth by shading, thus reducing the amounts of photosynthate available for rhizobia.

Table 3.5 Nitrogen fixed (kg N/ha/day) using acetylene reduction assay as affected by fertiliser treatments.

Site	**CONT**	**+S**	**+P**	**+N**	**+SP**	**+SN**	**+PN**	**+SPN**
LFLFM	0.48	0.28	0.59	0.25	1.00	0.34	0.39	0.42
HFHFM	0.43	0.58	0.20	0.07	0.48	0.10	0.12	0.16

The patterns of N fixed as affected by fertiliser treatments were similar to the patterns of legume yields, as discussed in the previous section. Like the patterns of legume yields, the +SP treatment was the most effective at fixing N_2, while N fertiliser applications had detrimental effects. The effects of fertiliser applications on the amount of N fixed were similar to other studies which have already shown that N fertilisation reduces N fixation (eg., Crush *et al.* 1982; Ledgard and Saunders, 1982; Mundy, 1987).

An interesting feature of these results is that the positive effects of the +SP treatment were a lot more pronounced at the LFLFM site, compared to the HFHFM site. At the LFLFM site, the +SP treatment more than doubled the amount of N fixed on the unfertilised control plot. As with legume growth patterns, the negative effect of N fertilisation appears to be more pronounced at the HF site than the LF site.

When the amounts of N fixed over spring 1990 were divided by the accumulated legume yields over the same season, the legumes on the HFHFM site appear to be more efficient at fixing N, compared to the legumes on the LFLFM site. Figure 3.7 shows that legumes on the HFHFM site fixed 0.19kg N/kg DM, while the legumes on the LFLFM site fixed 0.06kg N/kg DM. These results suggest that different species of legumes have different efficiencies for fixing N per unit mass. In a more detailed study of the botanical composition of the swards on similar sites at Ballantrae by del Pino Machado (1994), the swards on a site located on the LFLF farmlet showed a total herbage consisting of 4.2% white clover and 5.6% of other legume species. On a site located on the HFHF farmlet, 8.5% of the total herbage was white clover, and no other species of legume was found. While the legume species at the HFHFM sites were more efficient at fixing N per unit mass, the higher legume composition at the LFLFM meant that the total amount of N fixed was higher.

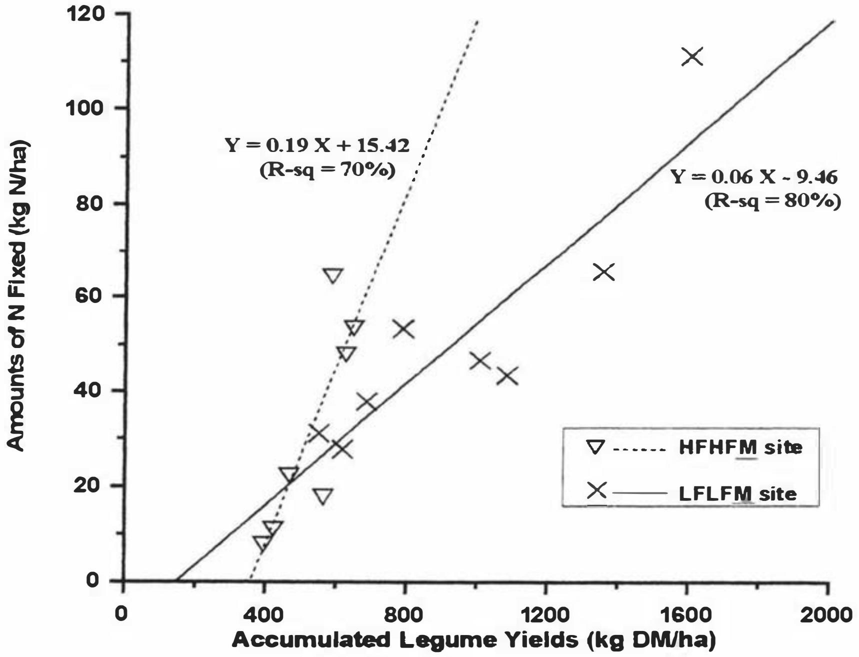


Figure 3.7 Relationships between the amounts of N fixed during spring 1990 and accumulated legume yields during the same season.

3.3.4 **Seasonal Yield Responses.**

In the Central North Island farming environment, livestock production is limited by winter carrying capacity. As mentioned in the discussion of the control plot yields, the most striking influence of the HF regimes on pasture growth is the more rapid pasture growth rates occurring in the autumn-winter period of each year (Fig. 3.1). This section examines whether winter carrying capacity at these sites could be increased with additional S, P, and/or N fertilisers. It is important to keep in mind that while applications of fertilisers may result in short-term increases in yield for a season, cost-benefit analysis which takes into account the farm balance sheet and long term aims, will always be required to justify fertiliser investment.

Seasonal pasture yield responses to fertiliser treatments are summarised in Table 3.6. There were no significant differences in total herbage yields between the control and +S plots except for individual cuts during summer 1990-91 on the LFLFL site (not shown in Table 3.6). It therefore appears, that there are generally adequate amounts of S at all these sites, due to the accumulation of mineralisable S in the soil organic matter. The SO_4^{2-} release patterns of these same soils in field lysimeter studies conducted by Sakadevan (1991) provide support for the findings. Application of S only, therefore, cannot be used to increase the carrying capacity of these farmlets through the slow growing seasons.

When S was applied in the presence of P (+SP), significant differences in pasture production were observed only on farmlets that had received no SSP fertiliser since 1980, especially in the LF sites. The low fertility, low slope site (LFNFL) produced significantly higher growth rates during spring and summer of both years, likewise, the low fertility, medium slope site (LFNFM) during winter 1990 and autumn 1991. A significant yield difference was observed on the HFNFL site during summer 1991-92 and also on the HFNFM site during spring 1990. In contrast, the sites on farmlets which had continued with SSP application since 1980 did not respond to +SP application. There were no significant differences in pasture production between the +SP plots and the control plots in the farmlets which continued to receive fertiliser, except for the LFLFM site in the summer of 1991-1992.. The diminishing residual value of SSP fertiliser applied about a decade earlier at the LF farmlets is reflected in these results. Where SSP has not been applied for over ten years, coupled with a low rate of previous applications (about 125kg SSP/ha over about five years), it is possible to increase the carrying capacity through winter and autumn by renewed application of S together with P.

Table 3.6 Summary of seasonal responsive sites to +SP and +SPN treatments at Ballantrae.

	Seasonal responsive trial sites to:	
Seasons	**+SP Treatment**	**+SPN Treatment**
Autumn 1990	-	LFLFL, LFLFM, HFNFL
Winter 1990	LFNFM	HFNFM
Spring 1990	LFNFL, HFNFM	LFNFL, LFLFL, HFNFL, HFNFM
Summer 1990-1991	LFNFL	LFNFL, LFNFM, LFLFL, HFHFL
Autumn 1991	LFNFM	LFNFL
Winter 1991	-	-
Spring 1991	LFNFL	LFNFL, LFLFL, LFLFM, HFHFL, HFHFM
Summer 1991-1992	LFNFL, LFLFM, HFNFL	LFNFL, LFLFL, LFLFM
Autumn 1992	-	-

Where S, P, and N were all applied together (+SPN), a pasture growth response was produced during autumn and winter 1990 on both sites located in the LFLF farmlet and the sites located in the HFNF farmlet. Pasture growth improved also on one of the sites located in the LFNF farmlet during autumn 1991. It is therefore possible to increase carrying capacity during the slow growing seasons by applying S, P, and N together on soils where previous fertiliser applications were of low rates, or, when applications have been discontinued for about ten years.

3.4 SUMMARY AND DISCUSSION

The range of continuous or withdrawn SSP fertiliser histories at the Ballantrae farmlets, have resulted in a range of soil fertility regimes. Trial sites can be found that vary almost three fold in annual rates of pasture production between the LFNF and the HFHF regimes. Despite SSP withdrawal and other studies reporting S losses from these farmlets that are greater than P losses (eg., Lambert *et al.*, 1988; Saggar *et al.*, 1990a, 1990b), overall pasture growth remains generally unresponsive to applied S (+S above the unfertilised control), even in the presence of P (+SP above +P). In Chapter Four, soil testing will be used to investigate this lack of responsiveness.

It appears that withdrawal of SSP affected pasture growth at the LF regime more than the HF regime (Fig 3.2). This is reflected by the differences between pasture yields on the sites located on the HFHF farmlets and those located on the HFNF farmlets, being generally less than the differences between the sites located on the LFLF and those located on the LFNF farmlets (Fig. 3.2). This is probably due to the relatively high amounts of N that are fixed at the LF farmlets and the more significant role that the low fertility, tolerant legumes play in the N economy of these swards (Fig. 3.7). This is also reflected in the results showing that the detrimental effect of N fertiliser on legume growth, outweighed the positive effect of S and P at the HF sites, but not at the LF sites.

It is concluded that legume growth at these plot trials was limited primarily by P. However, the utilisation of soil P for legume growth, was dependent on the supply of soil S. The results reported here suggest that there is adequate soil S supply at these sites to utilise soil P, indicated by the lack of legume response to the +S treatment. On the other hand, the same levels of soil S supply were not adequate to also utilise added fertiliser P in most situations. Sulphur fertiliser was therefore also required, as indicated by significant increases in legume growth and N_2 fixation under the +SP treatment. The problem now, is how to quantify the level of soil S supply (S availability) which is adequate for legumes to efficiently utilise *both soil and fertiliser P*. In the next chapter, several chemical extraction techniques are investigated for this purpose, using *actual yield* data on the unfertilised control plots as the pasture yield parameter.

In Chapter Five, the fertiliser treatment plot yield data will be used to expand on the models discussed in Chapter Four by transforming pasture yield into another parameter - *relative yield*. Actual yields on the unfertilised plots are again used in Chapter Seven to validate the use of a dynamic model that will be developed to simulate pasture growth as affected by daily climatological data.

It was shown in this chapter that, neither soil total S, total P, or total N can be used for predicting pasture yields. As suggested in the introduction of this chapter (section 3.1), an indicator of pasture yield must reflect the availability of N because the availability of N has *primary* effects on pasture growth, while S and P availabilities have mainly *secondary* effects. Before investigating different chemical soil extraction techniques to quantify S availability, a conceptual model is developed from the observed results reported in this chapter to enhance our understanding of the interaction between S and P availabilities, regulating the N economy of a grazed pasture system.

3.4.1 A Conceptual Model of the Interaction of S and P Availabilities* , Regulating the N Economy of a Grazed Pasture System.

In this section, the concepts of how pasture growth responds to improved S and P nutrition are reviewed and developed, in light of the pasture yield results of the 1990/1992-Ballantrae Trials. Sulphur and P fertiliser addition consistently stimulated legume growth more than grass growth. Nitrogen fertiliser addition on the other hand, stimulated total pasture growth but inhibited legume growth. The results in section 3.3.3 which showed that the detrimental effect of N on legume growth outweighed the positive effect of S and P application at the HF sites, but not at the LF sites, presumably due to the higher levels of soil inorganic N at the HF sites.

It has been established that N_2 fixation is inhibited by high levels of inorganic soil N (eg., Crush *et al.*, 1982; Ledgard and Saunders, 1982; Ledgard, 1989), as legumes will readily substitute N_2 fixation for uptake of inorganic soil N (Allos and Bartholomew, 1959). The utilisation of S and P for legume growth should therefore, also be influenced by available soil N.

The literature is silent on studies which specifically assess the response of mixed swards to S and P fertiliser in terms of available N. Likewise, mixed sward studies where the grass requirement for S and P to assimilate N, is isolated from the legume requirements for promoting N_2 fixation, appear absent from the literature. Therefore, the opportunity is taken here to make use of these aspects of legume-based pastures as the basis of a conceptual model, to develop further understanding of the interaction

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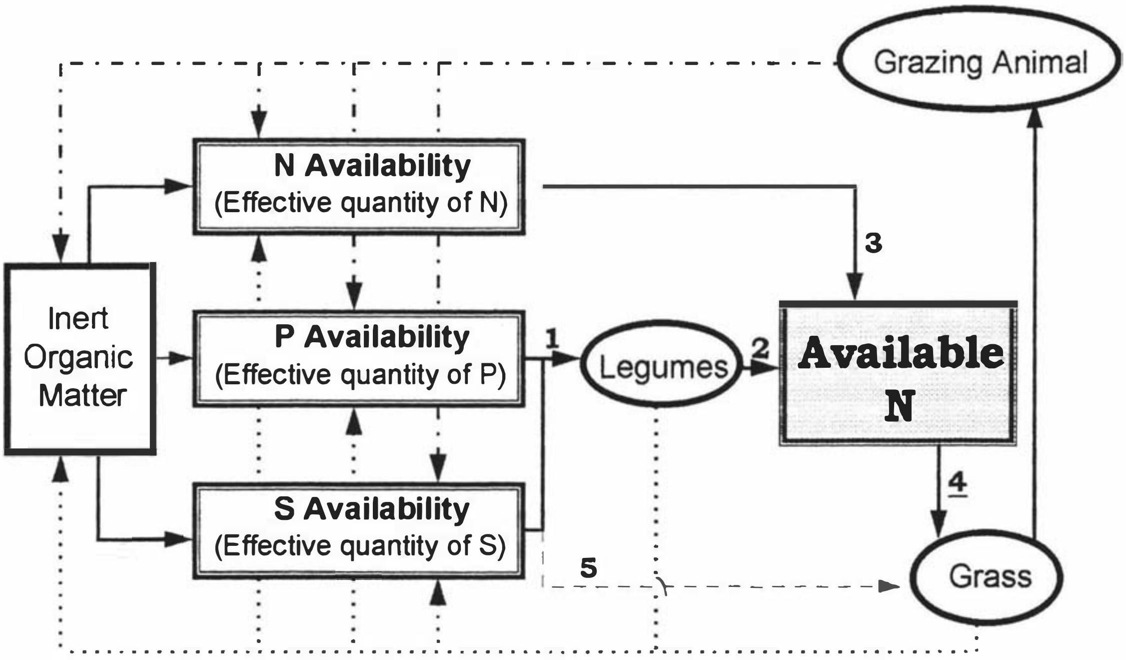
* For definitions of the words 'availability' and 'available', see Chapter One, p.5.

between S and P, regulating the N economy of the swards. It will also provide a basis for discussing the soil test models presented later to explain pasture response to S, P, and N fertilisers.



Processes **2, 3,** and **4** = N flows
Processes **1** and **5** = S plus P flows
– · – · – · – · = S, P, and N returns from animal excreta
· · · · · · · · · · · · = S, P, and N returns from dead plant material

Figure 3.8 Diagrammatic representation of the S, P, and N cycles in a grazed pasture system.

The principal interactions between S, P and N availabilities in a grazed pasture system are presented as a nutrient cycle in Figure 3.8. Processes labelled **4** and **5** represent the flow of available nutrients absorbed by grass. Processes labelled **1** and **3** represent the flow of the effective quantities of the nutrients supplied by the soil, estimated as the indices of nutrient availabilities. Process **2** represents the flow of N that was fixed by legumes.

The interactions between S, P, and N cycles are very complex in real systems. Therefore, for the purpose of modelling, some simplifications have to be made. The assumptions made include:

i) N assimilated by legumes are originated from fixed N, with negligible contribution from indigenous soil N.

ii) The demand of the grass component for N far outweighs the usage of inorganic N by legumes, hence, process **2** is not reversible.

iii) S and P uptake by grass are considered to be adequate for assimilation of available N and protein synthesis requirements at all times, hence, variations in S and P flows (process **5**) have negligible 'direct' effects on pasture yields within a season.

Evidence in support of assumption i) lies with many the studies showing that legumes frequently derive between 70 to 97% of their N symbiotically (eg., Haystead and Lowe, 1977; Edmeades and Goh, 1978; Crush *et al.*,1982; Ledgard and Saunders, 1982; Bergersen and Turner, 1983; Ledgard, 1989).

It has also been clearly established that as pasture development proceeds, N availability (Process **3**) increases while N inputs by symbiotic fixation (Process **2**) decline (Ball *et al.*, 1979; Ball and Field, 1985). This was further supported by the results in section 3.3.4 where the detrimental effect of N fertiliser on N fixation was more pronounced in the HFHF<u>M</u> site than the LFLF<u>M</u> site. Therefore, the need for fixed N appears to decline with a progressive decline in the contribution of legumes to total yield, as legume growth is suppressed by greater competition from grass associates at increased levels of N availability. Assumption i) proposes that the reduction in legume growth as soil fertility improves (see Figure 2.2), is significant enough to consider the assimilation of soil N by legumes as negligible, hence for simplification, there is no flow from the effective quantities of N to legumes in Figure 3.8.

Assumption ii) is supported by the results reported in section 3.3.4, which show that the contribution of legume yields (Table 3.5) to total yields (Table 3.4) ranged from only 6 to 8% at all sites. Similar results were obtained by Mackay *et al.* (1988). Therefore, the relationships between pasture yields and fertility of soils can be simplified and represented by the relationship between available N and grass yields only (Process **4**), without any flow of available N back to legumes.

The third assumption iii), implies that the amounts of S and P taken up by grass are either adequate or in excess of the amounts required for the assimilation of available N absorbed by plants during all seasons. It has been established that grass is a much stronger accumulator of sulphate S than legumes (Walker, 1957; Walker and Adams, 1958; Nguyen *et al.*, 1989a). The accumulation of sulphate S in grass indicates excess uptake of sulphate S from the soil that is not required by plants for protein synthesis despite the important role of S as an essential protein constituent. Similarly, P absorbed in excess of immediate requirements for growth is accumulated as inorganic P (Chapin *et al.*, 1982, Caradus, 1991) in the vacuole of plant tissue as excess P (Bieleski, 1973). The assumption that P is adequate for N assimilation, may not hold for soils with low soil P status, but since most farms with low soil P status cannot be maintained economically, the assumption can therefore hold for most situations.

Provided the above assumptions hold, this conceptual model hypothesises that pasture yield is a function of available N only (process labelled **4** in Figure 3.8); where available N is a consequence of S and P availabilities over a longer term (years). It implies that the term *deficiency* in this conceptual model, when associated with S or P nutrients, means S or P status where N fixation is limiting, rather than limitations on the S or P nutrition of grass, limiting the assimilation of N during processes of protein synthesis and cell metabolism.

This conceptual model also implies that estimates of S fertiliser requirements should be made only on the basis of whether there is adequate soil S supply to utilise available soil P and fertiliser P. From this perspective, the lack of response to the +S treatment at all sites while three of the four sites were responsive to the +SP treatment appears to suggest that S deficiency occurs only by induction with P application. This aspect of legume based pastures is emphasised throughout this thesis. The main aim of soil testing in this thesis is to find methods of predicting if application of P will induce an S deficiency or not.

In essence , S as a growth factor, is not exclusive of P, and vice versa. It is therefore, naive to put efforts into studying the effects of S nutrient on pasture growth in isolation.

CHAPTER FOUR

CHEMICAL EXTRACTION TECHNIQUES TO ASSESS SULPHUR AVAILABILITY: THE CHARACTERISATION OF SULPHUR AND PHOSPHOROUS AVAILABILITY AT THE BALLANTRAE SITES

4.1 INTRODUCTION

In the initial planning phase of this thesis it was anticipated that the pastures in the low fertility farmlets at Ballantrae would be singularly responsive to S topdressing. The S soil tests developed in this chapter concurrently with the ongoing pasture trials were to be evaluated against the pasture response to S.

The yields reported in Chapter Three, from the dominantly ryegrass/legume based swards of the Ballantrae farmlets, however, appear to reflect the P and N economy of each trial site rather than the soil S supply. The results showed that it was only after the P deficiency was alleviated that S became a constraint factor, limiting only legume growth and N_2 fixation. An important feature of the results was that, even ten years after SSP application was terminated, there was adequate S supplied by the soils to utilise soil P for legume growth. In these situations, most plant available S must have been mineralised from the soil organic S pool. The pasture growth response to P rather than S indicates the possibility that both P and S availability varies in a parallel manner across the different fertility farmlets with P always being the key limiting element. Thus, the emphasis of this chapter has changed to investigate whether soil S tests can be used to reflect the variable but apparently adequate S supply in the control plot soils. In this chapter, static-empirical models are developed to test certain concepts involving S availability in grazed pasture systems.

Modelling the mineralisation and immobilisation of S, from and into the soil organic S pool have been conducted mainly by empirical modelling, using data from chemical extractants fitted by regression analysis to pasture yield data (eg., Saunders *et al.*, 1988; Blair *et al.*, 1991; Watkinson *et al.*, 1991), or by mechanistic modelling using mass balance equations (eg., Heng, 1991; Sakadevan, 1991).

Firstly, empirical models using chemical extractants and pasture yield data have been developed directly for the purposes of guiding agricultural management, ie., as diagnostic tools for fertiliser recommendations. These models are the simplest form of modelling, developed without necessarily demonstrating an understanding of pasture systems. Their use as predictive models have been limited because without knowledge of the underlying mechanisms, it is difficult to transfer them away from where data was collected.

Secondly, the mechanistic models of Heng (1991) and Sakadevan (1991) have predicted S leaching well, and therefore have potential to be developed further into models used as tools to predict future S fertiliser requirements. These models are dynamic in nature and are therefore closer to reality than static soil test models. With the continuing improvement of computer capabilities, future models of pasture systems will be shifting more and more to resemble the dynamic nature of the systems, especially with the success of modelling water balance and water transport in soils.

The challenge facing agricultural scientists now, is how to incorporate concepts formulated from empirical models into the development of dynamic and mechanistic models. A major part of this thesis is, therefore, devoted to the development of empirical models, despite their shortcomings. The emphasis is in developing better understanding of the concepts behind empirical models, to help in the design of the more reliable dynamic and mechanistic models.

The concepts are mainly focused onto the active-S pool described in the conceptual model of the S cycle, used to summarise the literature (Fig. 2.3). It is believed that the mechanisms involving the active-S pool, regulates the effective quantities of soil S that interact with P to stimulate legume growth, hence, N_2 fixation. The active-S pool proposed in the S cycle (Fig. 2.3), consists of a labile organic-S pool, microbial-S, and the sulphate-S pool (soil solution plus adsorbed).

Normally, in a development sequence of pasture soils using SSP, like at Ballantrae Research Station, it is expected that soil P status as measured by Olsen P test, gives good predictions of pasture yield (Moir et al, 1995). As shown in Chapter Three at two sites having +S, +P and +SP treatments, the utilisation of soil P for legume growth was limited by the availability of S. Therefore, it is believed that a soil S fraction which regulates the utilisation of available soil P to stimulate legume growth, may also be a good indicator of pasture yield. The objective of this chapter is to find a measure of extractable S, using chemical extraction techniques that is strongly correlated with the increasing soil P supply as indicated by Olsen P, i.e. a test that is as good or better than the Olsen P at predicting pasture yields. It is believed that a measure of extractable S that correlates with and pasture yields as well as the Olsen P test, represents the effective quantity of soil S (index of S availability) that utilises P for legume growth promoting N fixation.

In section 4.2.3, actual yield on the unfertilised control plots are regressed against the amounts of soil S in different chemical extractants, to examine whether the difference in pasture yields at Ballantrae sites caused by differences in farmlet fertiliser history, can be explained by the differences in S extracted. The ability of each soil S fraction to predict actual yields, are also compared with the Olsen P (section 4.2.3.8).

In order to design the extraction techniques, some knowledge of the underlying mechanisms involving the active-S pool is required, for the purpose of discussing why a soil S fraction can or cannot be used as an index of S availability, hence, as a predictor of pasture yield.

4.1.1 A Theoretical basis for S Availability

The conceptual model of the S cycle in a soil-plant-animal grazing system was presented diagrammatically in Figure 2.3. Figure 4.1 shows the soil component of the system assuming that this component is at a biochemically equilibrated state. For simplification, all important aspects of the S cycle which pertain to the availability of S (active-S pool), are represented by the transformations between the inert organic S, the labile organic S, and the sulphate-S fractions.

The assumptions taken to conceptually model the availability of S include:

i). That all transformations to and from the inert organic S fraction (**Org-S$_{inert}$**) to sulphate-S, proceed via a labile organic S fraction (**Org-S$_{labile}$**) (Fig 4.1).

* **Sul-S$_{eqm}$** is the sulphate-S level at equilibrium, which include both adsorbed and soluble sulphates.

Figure 4.1 Diagram of the biochemical equilibrium of S fractions in soil of pastoral system.

Compared to Figure 2.3, the diagrammatic representation of the biochemical quasi-equilibrium of soil S in Figure 4.1, suggests that the microbial-S pool is analogous to a catalyst in a chemical reaction, regulating the rates of the reaction, but itself is not a reactant or product of the reaction. Another feature of the soil system in Figure 4.1 is that the sulphate-S is considered as one pool, i.e., the transformation between adsorbed and soluble sulphate-S is very rapid, in terms of the time span considered by annual soil testing because sulphate-S can easily get desorbed from soil colloids. This pool, which is represented by $\textbf{Sul-S}_{\textbf{eqm}}$, reflects the level of sulphate-S in the field, in the absence of a heavy rainfall event resulting in leaching or a recent S fertiliser input.

ii) That $\textbf{Org-S}_{\textbf{labile}}$, the S pool that is subject to microbial attack, does not change in size with time, i.e., the system is at quasi equlibrium.

$$\frac{d\,(\textbf{Org-S}_{\textbf{labile}})}{dt} = k_{min}'\,(\textbf{Org-S}_{\textbf{inert}}) + k_{imm}\,(\textbf{Sul-S}_{\textbf{eqm}}) - k_{imm}'\,(\textbf{Org-S}_{\textbf{labile}}) - k_{min}\,(\textbf{Org-S}_{\textbf{labile}}) = 0.$$

Equation 4.1

$$\textbf{Org-S}_{\textbf{labile}} = \frac{k_{min}'\,(\textbf{Org-S}_{\textbf{inert}}) + k_{imm}\,(\textbf{Sul-S}_{\textbf{eqm}})}{(k_{imm}' + k_{min})}$$

Equation 4.2

iii) That the rate of mineralisation of $\textbf{Org-S}_{\textbf{inert}}$ to $\textbf{Org-S}_{\textbf{labile}}$ (processes 17, Fig. 2.3) is much slower than the rate of mineralisation of $\textbf{Org-S}_{\textbf{labile}}$ to $\textbf{Sul-S}_{\textbf{eqm}}$ (processes 2 and 9, Fig. 2.3), and the immobilisation of $\textbf{Org-S}_{\textbf{labile}}$ to $\textbf{Org-S}_{\textbf{inert}}$ (process 18, Fig. 2.3) is much slower than the immobilisation of $\textbf{Sul-S}_{\textbf{eqm}}$ to $\textbf{Org-S}_{\textbf{labile}}$ (processes 1 and 10, Fig. 2.3), ie., $k_{min}' \ll k_{min}$ and $k_{imm}' \ll k_{imm}$, hence Equation 4.2 becomes:

$$(\textbf{Org-S}_{\textbf{labile}}) = k_{imm} / k_{min}\,(\textbf{Sul-S}_{\textbf{eqm}})$$

Equation 4.3

or,

$$(\textbf{Sul-S}_{\textbf{eqm}}) = k_{min} / k_{imm}\,(\textbf{Org-S}_{\textbf{labile}}).$$

Equation 4.4

Equation 4.4 implies that **Sul-S$_{eqm}$**, is proportional to the size of **Org-S$_{labile}$**, with the proportionality constant being the ratio between the mineralisation and immobilisation rate constants, k_{min} and k_{imm} :

$$K_S = k_{min} / k_{imm}$$

Equation 4.5

K_S is analogous to the equilibrium constant of reversible first-order chemical reactions. In Figure 2.3, k_{min} and k_{imm} are shown to be mediated by microbial activity.

4.1.1.1 *Implications of the Concepts of S Availability on developing Chemical Extraction Techniques*

As described in the literature review (Chapter Two), soil tests based on sulphate-S can be affected dramatically by heavy rainfall (Ghani *et al.*, 1990), the presence of plants (Freney and Spencer, 1960; Nicholson, 1970; Tsuji and Goh, 1979; Maynard *et al.*, 1985), and the presence of excreta from grazing animals (Williams and Haynes, 1990; Haynes and Williams, 1991). However, while the soil sulphate-S pool may vary significantly over short periods of time (Blair, 1979) which makes soil tests based on sulphate-S unreliable, Figure 4.1 proposes that a sulphate-S pool (**Sul-S$_{eqm}$**) that is at equilibrium with labile organic S pool (**Org-S$_{labile}$**), may exist if there is no heavy rainfall and no fertiliser application. Evidence of the existence of **Sul-S$_{eqm}$**, is obtained from the results of Ghani *et al.* (1990), which show that in the absence of added sulphate-S from external sources like fertiliser, or excessive removal by leaching, sulphate-S levels varied only by about 1mg S/kg soil over several months. Watkinson and Perrott (1990) also postulated the existence of a 'quasi steady-state' that produces relatively constant concentrations of sulphate-S but did not demonstrate how this quasi steady-state is stabilised.

If all these assumptions hold, then the ratio between mineralisation rates and immobilisation rates, must be constant for all soils and defined by K_S, (Eqn. 4.5).

Therefore, in search of a soil test that measures part of the soil organic S pool, it appears that any improvement would be related to the ratio of inorganic/organic S extracted, rather than the specific extractant chemistry. This is expressed in Equations 4.3 and 4.4, which suggests that a soil S test which extracts a soil S fraction with both **Sul-S$_{eqm}$** and **Org-S$_{labile}$** would be a better index of S availability than a soil test that is based on either one of the fractions.

4.2 RANKING CHEMICAL EXTRACTANTS FOR BEST INDEX OF SULPHUR AVAILABILITY

Sub-samples from the core samples (0-75mm) collected at the beginning of the Ballantrae field trial experiments from all the plots, before fertiliser application were bulked after air drying and sieving (<2mm). These bulked samples were used for chemical analysis presented here, unless otherwise stated.

4.2.1 Analysis of sulphate-S

S extracted in all the extractants discussed below were determined by reduction to hydrogen sulphide at 120^{O}C with a strong reducing mixture of hydriodic acid, hypophosphoric acid and formic acid, using a modification of the method of Johnson and Nishita (1952) (CSIRO Division of Forest Research, Method No. PS17), on an autoanalyser (Technicon, Series II).

4.2.2 **Mathematical Equations Fitted**

One of the problems in selecting mathematical equations that should be used to represent the relationship between yield data and indices of availability is that the data may be fitted equally well by diverse equations. The commonly used coefficient of determination (R^2) test for goodness of fit may yield comparatively similar values for several equations. Colwell (1983) illustrated this problem by using each of nine equations to represent two sets of experimental data yielding response curves differing in shape. Cerrato and Blackmer (1990) published a similar graphic comparison of the fit of five different equations to a given set of data.

In this chapter, three mathematical equations are tested for their ability to model the relationships between various indices of S availability and the pasture yield data presented in Chapter Three. The equations are:

(i) $y = \boldsymbol{a}(1 - e^{\boldsymbol{bx}})$ Equation 4.6

(ii) $y = \boldsymbol{a} + \boldsymbol{b}\ln x$ Equation 4.7

(iii) $y = \boldsymbol{a} + \boldsymbol{b}x$. Equation 4.8

In these equations, $\boldsymbol{a}$ and $\boldsymbol{b}$ are constants fitted by the method of least-squares, x is the chemical soil test to be assessed as an index of S availability or the Olsen P value, as the index of P availability, y is a pasture yield parameter. It is important to emphasise that these equations are empirical, because they offer no description of the processes involved in the growth of pasture as affected by S or P availability.

Both Equations 4.6 and 4.7 are curvilinear functions, while Equation 4.8 is the linear relationship. Equation 4.6 is a Mitscherlich type equation using the concept that the rate of increase in yield produced with increasing nutrient availability is proportional to the decrement from the maximum yield. Equation 4.7 is the same type of equation used by Saunders *et al.* (1988) to compare soil tests for predicting S status in New Zealand pastures and by Saunders *et al.* (1987) to compare soil tests to predict P status of New Zealand pastures, using *relative yield* as the pasture yield parameter.

4.2.3 Developing Soil Test Models using Actual Yield as the Pasture Yield parameter

In this section, soil test models are developed, using regression analysis between *actual yield* as the pasture yield parameter and extractable soil S from various chemical extraction techniques. The results using soil extractable S are compared with the result using the Olsen P soil test to develop some understanding of the interaction between S and P, which regulates the N economy of the swards. A conceptual model based on these findings, is presented in section 5.1.1 of the next chapter.

The use of actual accumulated yield rather than relative yield as the pasture yield parameter in this chapter, is possible because the trials were all located on soils of the same type, under similar climatic conditions, with the only differences being that of fertility due to different fertiliser histories and stock behaviour (section 3.3.1).

4.2.3.1 *Calcium phosphate extractable S: Ca-P$_{(0.04M)}$*

In New Zealand, S fertiliser recommendations are made using 0.01M $Ca(H_2PO_4)_2$ extractants (Saunders *et al.*, 1981) (section 4.2.3.7). The New Zealand Soil Bureau on the other hand, adopted the use of 0.04M $Ca(H_2PO_4)_2$, for more complete extraction of sulphate from highly anion-retentive soils (Searle, 1979). While the amounts of sulphate in 0.04M $Ca(H_2PO_4)_2$ extracts were mainly used for soil characterisation purposes, they also could be used to indicate S deficiencies (Searle, 1988).

Method

The extraction solution was 0.04M $Ca(H_2PO_4)_2$, extracting for 30min on an end over end shaker using a soil:solution ratio of 1:20.

Results and Discussion

The amounts of sulphate-S extracted are given in Table 4.1. The relationships between these amounts of S extracted and annual accumulated yields (Fig. 4.2a,b,c) were explored, using the three mathematical equations described above (Eqns. 4.6 - 4.8).

The results indicate that the amounts of solution plus adsorbed sulphate-S in these soils generally fall into two groups; <15mg S/kg soil and > 30mg S/kg soil. Such a distribution of data is not conducive to testing these regression models over the range of 15mg S/kg soil to 30mg S/kg soil. While the amounts of S extracted correlated fairly well with Olsen P (R^2 = 73%, Table 4.5), this extractant, which is referred to as Ca-$P_{(0.04M)}$ from here on, gave poor explanations of annual accumulated yields on the control plots, compared to the Olsen P soil test (Tables 4.2 - 4.4).

The poor performance of the Ca-$P_{(0.04M)}$ soil test to predict pasture yield, is believed to be related to the inability of the test to extract a mineralisable pool of organic S (**Org-S_{labile}**) that supplies most of plant available S.

4.2.3.2 *Potassium Chloride extractable S: $KCl_{(16hr)}$*

When the amount of adsorbed sulphate is negligible, an extractant which employs an anion that is not adsorbed strongly on the soil sulphate sorption sites such as chloride, should be adequate to extract readily soluble sulphate-S (Williams and Steinbergs, 1959, 1962; Bettany *et al.*, 1974). Amounts of sulphate in $CaCl_2$ extracts were found to correlate well with the amounts of S mineralised during laboratory incubation experiments (Barrow, 1961; Kowalenko and Lowe, 1975; Tsuji and Goh, 1979), but correlated poorly with plant uptake (Tsuji and Goh, 1975) and yield response in field conditions, where soils were sulphate retentive (Nguyen, 1982).

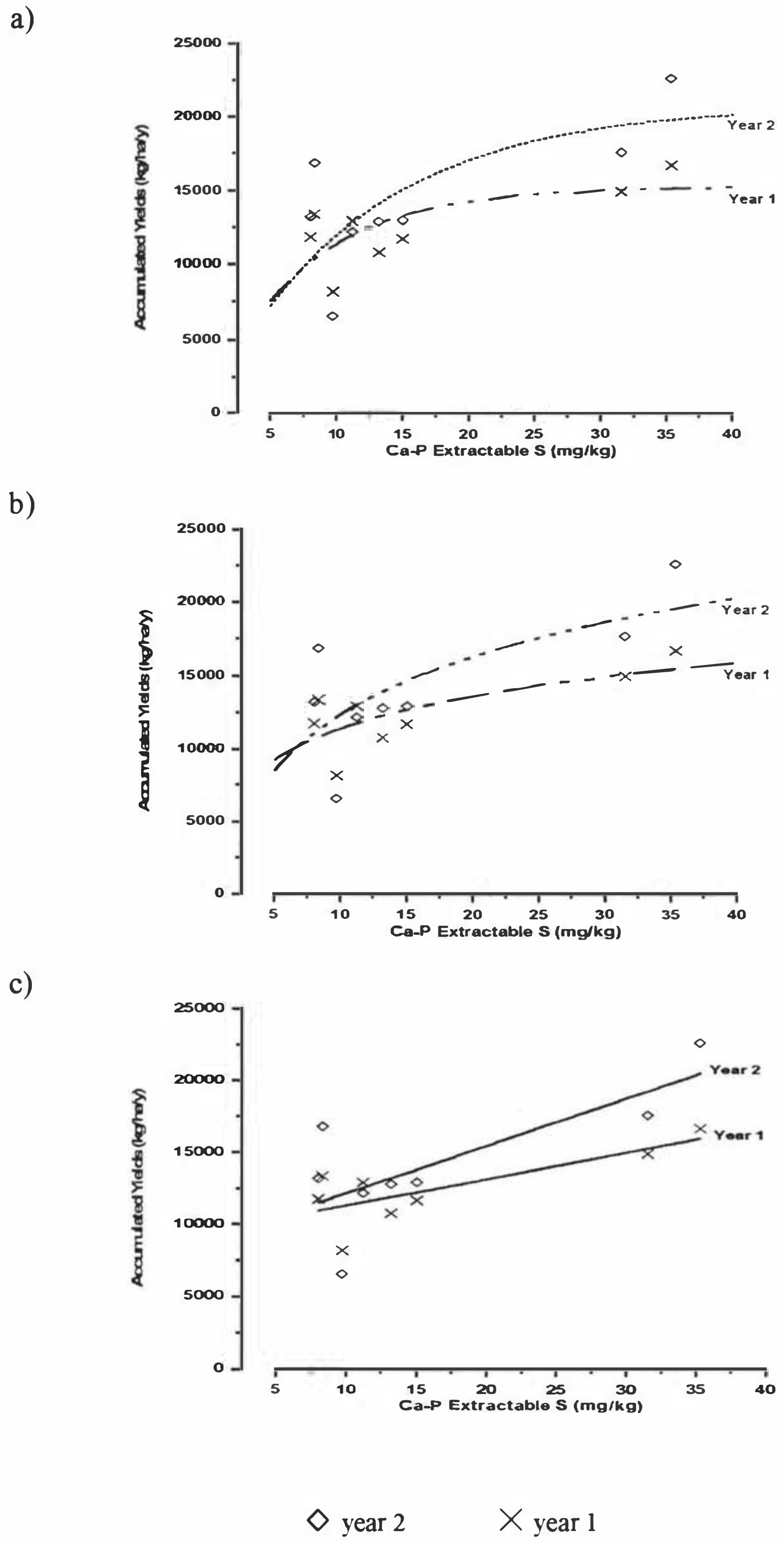


Figure 4.2 Regressions between annual accumulated yields and the amounts of S extracted by **0.04 M $Ca(H_2PO_4)_2$ extractable S: Ca-$P_{(0.04M)}$**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

By heating up the chloride extractant during extraction procedure, it was also found that the chloride anion is capable of also extracting fractions of organic S. Blair *et al.* (1991) reported the use of 0.25M KCl heated for 3hr at temperatures varying from 25 to 100°C. They found that the amounts of S in extract at 40°C correlated well with yield response in the field.

As mentioned in section 4.1.1, the adsorption and desorption of sulphate to and from soil colloids, may be considered as so rapid in terms of the time span considered by soil testing, so that the sulphate-S pool may be considered as just one pool (**Sul-S$_{eqm}$**, Fig. 4.1). The amounts of S in a chloride extractant, using an overnight extraction procedure, was therefore considered as worth investigating.

Method

Duplicate two grams of topsoil were weighed into 50ml centrifuge tubes, add 40ml 0.5M KCl solution, then shake on an end over end shaker in a cabinet with controlled temperature, set at 25^{0}C for 16 hours. The extracts were centrifuged at 10000rpm for 10min before filtering through a Whatman 42 filter paper. The filtrates were then analysed for S as described above.

Results and Discussion

The amounts of S extracted were generally higher than Ca-P$_{(0.04M)}$ except for the two HFHF sites (Table 4.1). When related to annual accumulated yields on the control plots (Fig. 4.3a,b,c), this soil test performed better than the Olsen P soil test (R^2 ranging from 61.2% using Year 1 data fitted with Equation 4.7 to 68.6% using Year 2 data fitted with Equation 4.9, Tables 4.2-4.4). However, the scatter of data points between 13 and 20mg S/kg soil were grouped. This distribution of data therefore, may not be conducive to this soil test having diagnostic value for soils between 13 and 20mg S/kg soil.

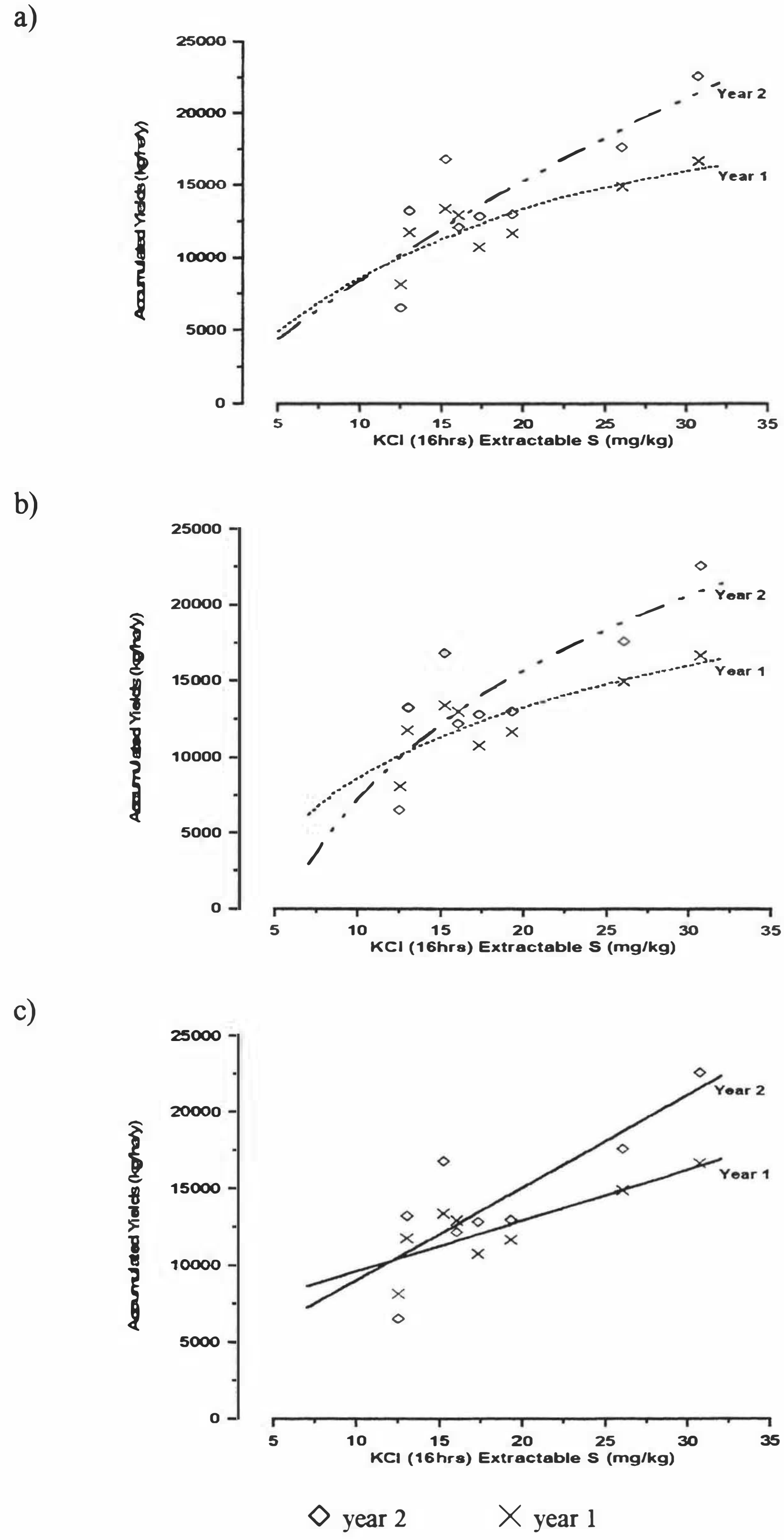


Figure 4.3 Regressions between annual accumulated yields and the amounts of S extracted by **<u>Potassium Chloride extracted for 16 hrs: KCl$_{(16hr)}$</u>**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

Raised controlled temperature conditions for routine soil analysis is likely to create handling problems. For this reason, raising the temperature of KCl extractions to extract fractions of organic S, were not undertaken in this study. Preference was given to using mild oxidation reagents with KCl, at room temperature (sections 4.2.3.4 - 4.2.3.6).

4.2.3.3 *Anion exchange resin: $AER_{(Cl^-)}$*

The use of ion exchange membrane resins for soil extractions have been shown to have more practical advantage over extractions with solvents because they are tidier and are easy to prepare (Searle, 1988; Saggar, 1990).

During turbidimetric measurement of sulphate in $Ca(H_2PO_4)_2$ solutions, there is often interferences due to organic matter in the extracts. Searle (1988) reported the use of an anion exchange membrane in phosphate form for extracting sulphate without interferences because no organic matter is present in the membrane method. His results showed strong correlations between the membrane extractable S and both the 0.01M and 0.04M $Ca(H_2PO_4)_2$ extracts.

As the $Ca\text{-}P_{(0.04M)}$ soil test showed poor coefficients of determination (R^2) values when regressed against annual accumulated yields on the control plots (section 4.2.3.1), it was therefore expected that the exchange membrane resins in phosphate form, would also perform poorly. The $KCl_{(16hr)}$ soil test on the other hand showed better R^2 values (Tables 4.2 - 4.4), prompting the use of exchange membrane resins in chloride form as a possible method that may be used as an index of S availability.

Method

Preparation of resin strips: The anion exchange membranes (BDH Chemicals Ltd., England) were cut into 62.5mm strips long and 25mm wide providing a reactive surface of 3125mm^2. The resin strips were converted to Cl^- form by placing them in a beaker containing 0.5M HCl with a volume equivalent to 200ml per strip and stirred occasionally for 1hr. This was repeated with fresh solution for another hour, then washed twice with deionised water. The strips were then ready for use. After use, the strips were regenerated by washing them thoroughly 2-3 times with deionised water then converting them to Cl^- form again as described above.

Extraction and elution: Triplicate one gram samples of soil were weighed into 50ml centrifuge tubes, 25ml of deionised water was added followed by a Cl^- ion exchange strip. The tube was shaken end over end for 16 hours in an enclosed cabinet with its temperature set at 20^0 C. The strips were removed with tweezers, washed with deionised water to remove adhering root and soil materials, then transferred to clean 50ml centrifuge tubes containing 20ml, 0.5M KCl and shaken on an end over end shaker for 3hr. The sulphate-S eluted was analysed as described above.

Results and Discussion

The amounts of S extracted were in a similar range to the amounts that were extracted with $KCl_{(16hr)}$ (Table 4.1), but correlated poorly (R^2 = 53%) with the Olsen P test compared to $KCl_{(16hr)}$ (R^2 = 74%) (Table 4.5). Although this method had practical advantages over chemical solution extraction procedures, the amounts of S extracted regressed poorly against annual accumulated yields on the control plots, compared with Olsen P and other soil S tests (Tables 4.2 - 4.4), using the three mathematical equations described above (Eqns. 4.6 - 4.8).

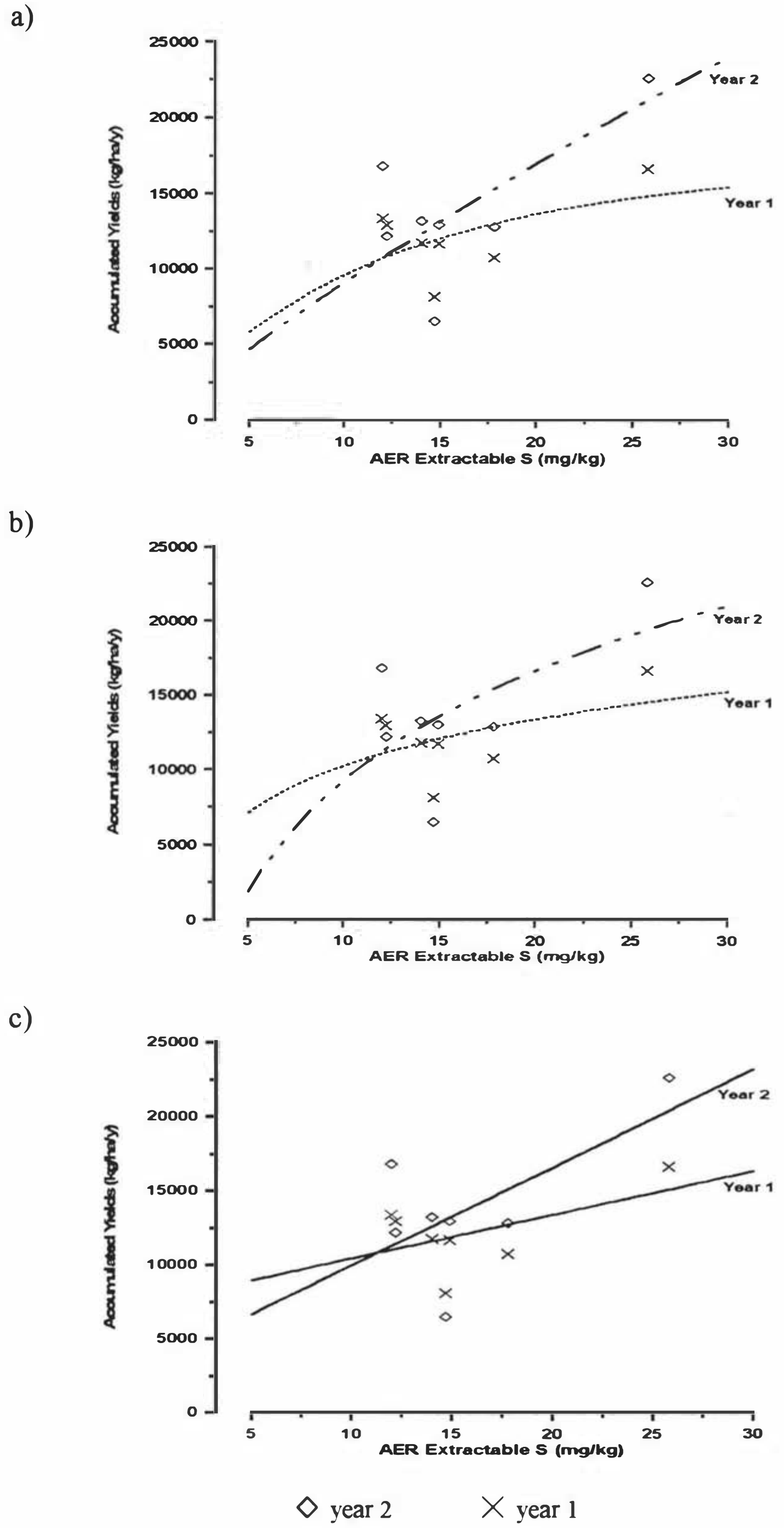


Figure 4.4 Regressions between annual accumulated yields and the amounts of S extracted by **Anion Exchange-Membrane Resin: AER$_{(Cl^-)}$**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

4.2.3.4 *H_2O_2 oxidation/KCl extraction: 4%H_2O_2/$KCl_{(16hr)}$*

Hydrogen peroxide is a mild oxidising agent adopted to oxidise different fractions of soil organic matter, depending on its concentration. For a given concentration of hydrogen peroxide, only certain organic compounds are susceptible to oxidation, while the more stable organic compounds are not. For each soil sample therefore, the organic compounds oxidised, are hopefully proportional to those that are susceptible to microbial decomposition in the field, **Org-S_{labile}**, while the more stable organic compounds, **Org-S_{inert}**, are not oxidised, thus, simulating the compounds resistant to decomposition.

Preliminary Studies

Effect of time and extractants: Topsoil samples from the LFLFM site, after drying and sieving (<2mm), were used for a preliminary study. Two grams of soil were pre-extracted with 40ml, 0.5M KCl and 0.04M $Ca(H_2PO_4)_2$ for 16hr, on an end over end shaker, to ensure that all sulphate-S was removed. After decanting, the residue was treated with 2% hydrogen peroxide for different periods of time, and extracted again with KCl and with Ca-P.

The results (Fig. 4.5) shows that KCl extracted more S than Ca-P, probably due to the better soil dispersion in K^+ solution than in Ca^{2+}. Both the amounts of S extracted with KCl or Ca-P increased with increasing time of oxidation, and then levelled off after 16 hours. A 16 hour oxidation/extraction time was chosen for further study.

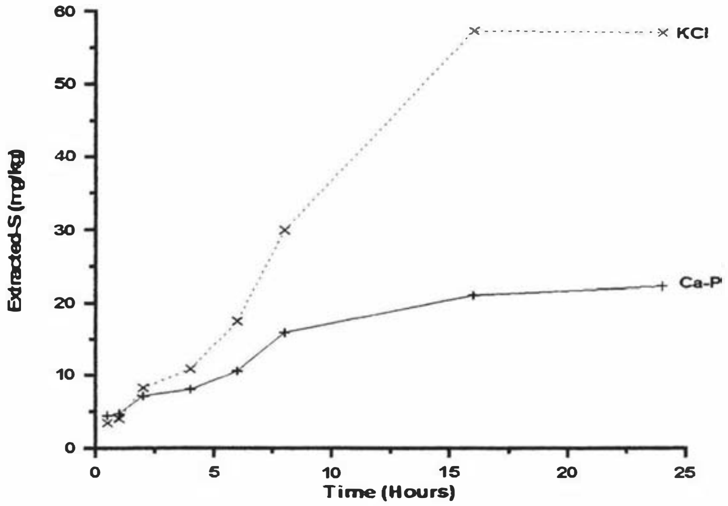


Figure 4.5 Amounts of S extracted with either 2%H_2O_2/KCl or2%H_2O_2/Ca-P with increasing oxidation time.

Effect of H_2O_2 concentration: Topsoil samples from the HFNF farmlets, collected from different slopes of 0-12°, 13-25°, after drying and sieving (<2mm) were used for this preliminary study. Two grams soils were pre-extracted with 40ml, 0.5M KCl for 1hr, centrifuged at 10000rpm for 10min and decanted. To the residues, 5ml of different concentrations of H_2O_2 plus 35ml KCl were added so that the final concentrations of H_2O_2 varied from 0% to 4.0%. The mixtures were then shaken for 16hr on an end over end shaker, centrifuged at 10000rpm, filtered through Whatman 42 filter paper and analysed for S as described above.

The results (Fig. 4.6) show that the amounts of S extracted increased with increasing concentration of the oxidising agent, but then levels off. It was decided that a concentration of 4% may be adequate to oxidise the labile organic S pool, **Org-S$_{labile}$**, from all soils without oxidising inert organic S, **Org-S$_{inert}$**, that would not be susceptible to biological decomposition in the field. This combined oxidation and extraction procedure was therefore, adopted for further study.

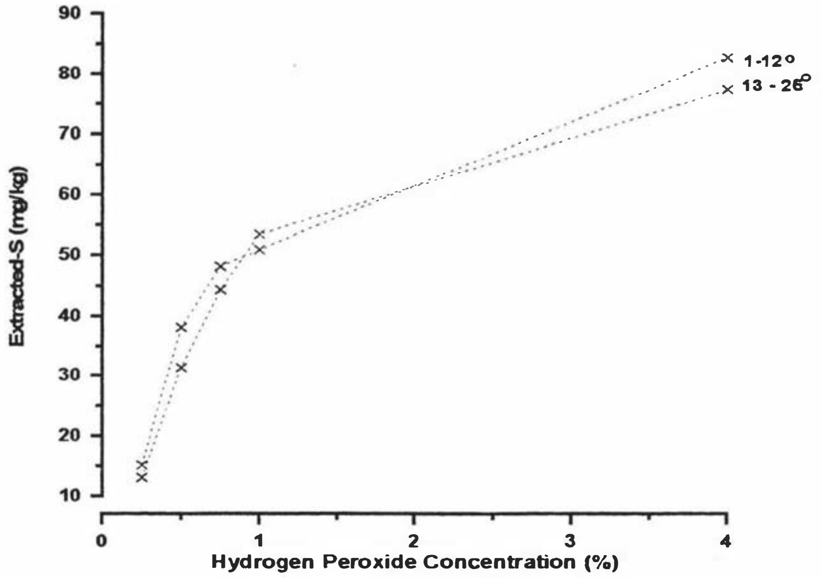


Figure 4.6 Amounts of S oxidised and extracted with increasing H_2O_2 concentration.

Method: Simultaneous Oxidation and Extraction

Triplicate one gram soil samples were weighed into 50ml centrifuge tubes, add 20ml 4% H_2O_2\0.5N KCl mixture and shake for 16hr using an end over end shaker. The extracts were centrifuged at 10000rpm for 10min, filtered through Whatman 42 filter paper and analysed for S as described above.

Results and Discussion

The amounts of S extracted are given in Table 4.1 and the relationships with annual accumulated yield shown in Figures 4.7a,b,c. This test extracts both sulphate-S, plus some organic S. As hypothesised in section 4.1.1.1, it performs better than the extractants that are based on either sulphate-S or labile organic S only (Tables 4.2 - 4.4). It also correlated well with Olsen P (R^2 = 77%, Table 4.5) and even performed better than the Olsen P soil test when regressed against annual accumulated yields on the control plots (Tables 4.2-4.4).

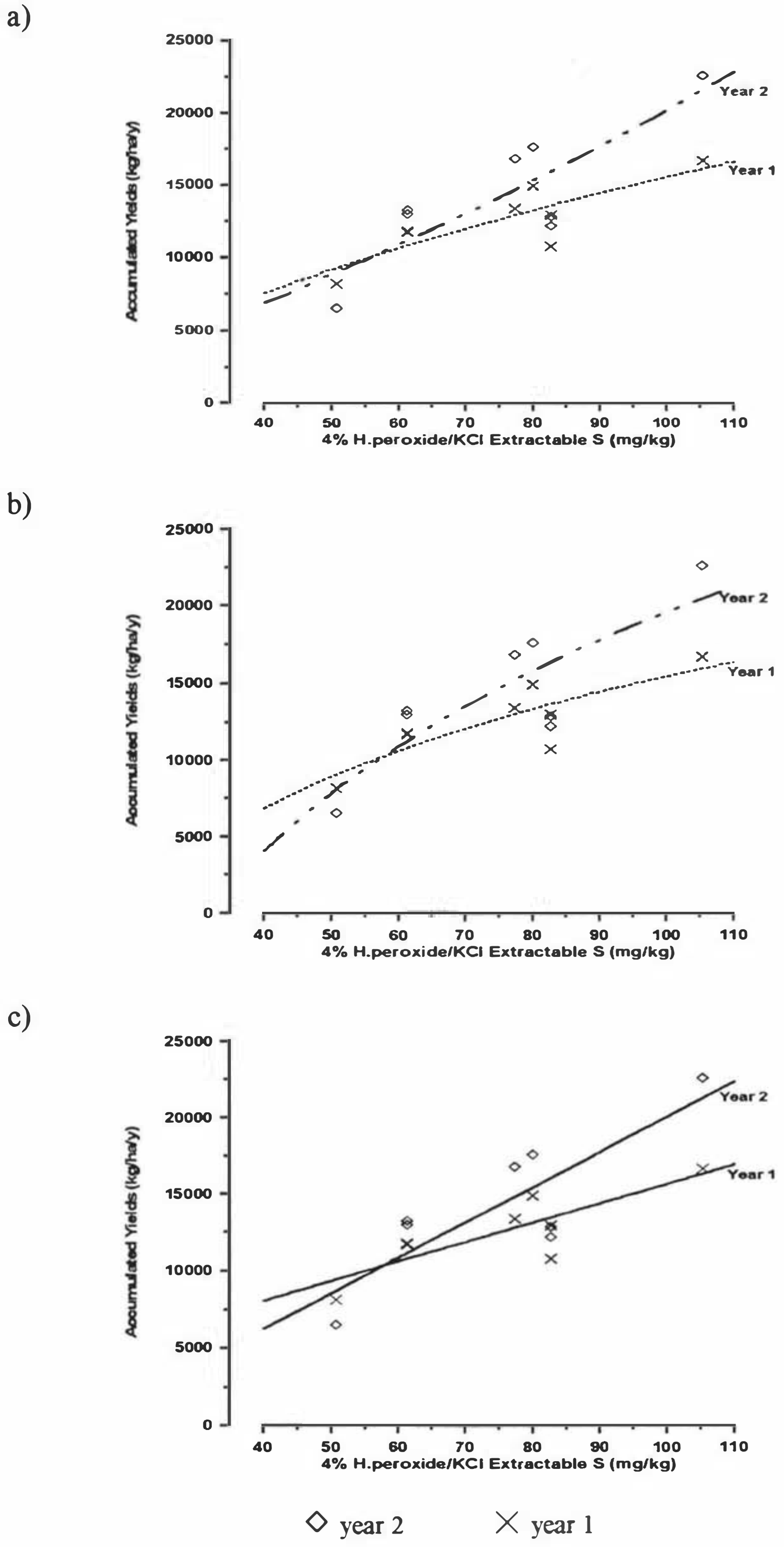


Figure 4.7 Regressions between annual accumulated yields and the amounts of S extracted by **Hydrogen peroxide/Potassium chloride: 4% O_2/$KCl_{(16hr)}$**, using:

a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$
(See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

The amounts of S extracted were also about 4-5 times more than the amounts extracted with the $KCl_{(16hr)}$ at 25°C, extracting 4.6 - 14.1% of total S, compared to 1.1 - 4.1% extracted by the $KCl_{(16hr)}$ soil test (Table 4.1). Interestingly, its performance was only slightly better than the $KCl_{(16hr)}$ soil test, when comparing the R^2 values from regression analysis against annual accumulated yield on the control plots, using Equations 4.6 - 4.8 (Tables 4.2 - 4.4). However, this soil test showed a better scatter of data points, with the sites not being polarised into two groups as observed with the previous extracts.

4.2.3.5 *Sequential A: $KCl_{(1hr)}$ followed by 4%H_2O_2/$KCl_{(16hr)}$*

To compare soil tests that either extract **$Sul\text{-}S_{eqm}$** or **$Org\text{-}S_{labile}$** alone, with soil tests that extract and measures both S fractions, sequential extractions were conducted. The first sequential extraction experiment, reported in this section as Sequential A, uses the first extraction to extract **$Sul\text{-}S_{eqm}$** only. In contrast, the second sequential experiment, reported as Sequential B in section 4.2.3.6, uses the first extraction to extract a very small amount of organic S together with **$Sul\text{-}S_{eqm}$**, while the second extract contains a much larger fraction from organic S.

Method

Duplicate two grams samples of soil were pre-extracted with 40ml 0.5MKCl in 50ml centrifuge tubes for 1hr on an end over end shaker. After centrifuging, the supernatants were decanted, and analysed for S. To the residues, 40mls mixture of 4%H_2O_2/0.5MKCl were added and shaken for 16hrs using an end over end shaker. The mixtures were then centrifuged at 10000rpm for 10min, filtered through Whatman 42 filter paper and analysed for S as described above. The first and second extractants will be referred to as $KCl_{(1hr\text{-}1stA)}$ and 4%H_2O_2/$KCl_{(16hr\text{-}2ndA)}$ respectively from here on.

Results and Discussion

The amounts of S extracted are given in Table 4.1, with the sum of $KCl_{(1hr\text{-}1stA)}$ and $4\%H_2O_2/KCl_{(16hr\text{-}2ndA)}$ being referred to as $SeqA_{(Tot\text{-}S)}$ from here on. The amounts of S removed by the first extractant, $KCl_{(1hr\text{-}1stA)}$, were comparable to the amounts extracted with $Ca\text{-}P_{(0.04M)}$, but generally lower than the $KCl_{(16hr)}$ extract, indicating that the period for extraction with KCl does affect the amounts of S extracted.

The amounts of S contained in $SeqA_{(Tot\text{-}S)}$ ranged from 2.7 to 7.6% of total soil S, compared to aa range of 4.6 to 16.5% of total S in $4\%H_2O_2/KCl_{(16hr)}$. The effect of the $KCl_{(1hr\text{-}1stA)}$ pre-extraction appears to reduce the total amount of S oxidised by $4\%H_2O_2$ which suggest that oxidation of organic S may be controlled by end product. The reaction mechanism would be difficult to confirm in such complex mixtures. However, it is possible to speculate that the soil residue, after $KCl_{(1hr\text{-}1stA)}$ extractable S were removed, contained more K^+ ions than the soil samples before the $4\%H_2O_2/KCl_{(16hr)}$ extraction. This may have reduced the oxidising power of $4\%H_2O_2$[*] during the $4\%H_2O_2/KCl_{(16hr\text{-}2ndA)}$ extraction compared to the oxidising power of $4\%H_2O_2$ during the $4\%H_2O_2/KCl_{(16hr)}$ extraction which had less K^+ ions in the extraction mixture.

When the amounts of S in the Sequential A extracts were regressed against annual accumulated pasture yields on the control plots, using the three equations (Eqns. 4.6 - 4.8), it was observed that both the first extractant, which contains sulphate-S only, $KCl_{(1hr\text{-}1stA)}$ (Fig. 4.8a,b,c), and the second extractant, $4\%H_2O_2/KCl_{(16hr\text{-}2ndA)}$ (Fig. 4.9a,b,c), which contains labile organic S only, performed poorly (Tables 4.2 - 4.4) compared to $SeqA_{(Tot\text{-}S)}$ (Fig. 4.10a,b,c). As hypothesised, a soil test that combines **$Sul\text{-}S_{eqm}$** and **$Org\text{-}S_{labile}$** would perform better than a soil test based only on either fraction.

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[*] Hydrogen peroxide can act both as an oxidising agent and as a reducing agent; for example, it oxidises sulphurous acid to sulphuric acid,

$$H_2SO_3(aq) + 2H_2O_2(aq) \longrightarrow H_2SO_4(aq) + 2H_2O(l)$$

and reduces silver oxide to silver,

$$Ag_2O(s) + H_2O_2(aq) \longrightarrow H_2SO_4(aq) + 2H_2O(l).$$

(Chang, R. (1981). *Chemistry* (First Edition). Random House, Inc)

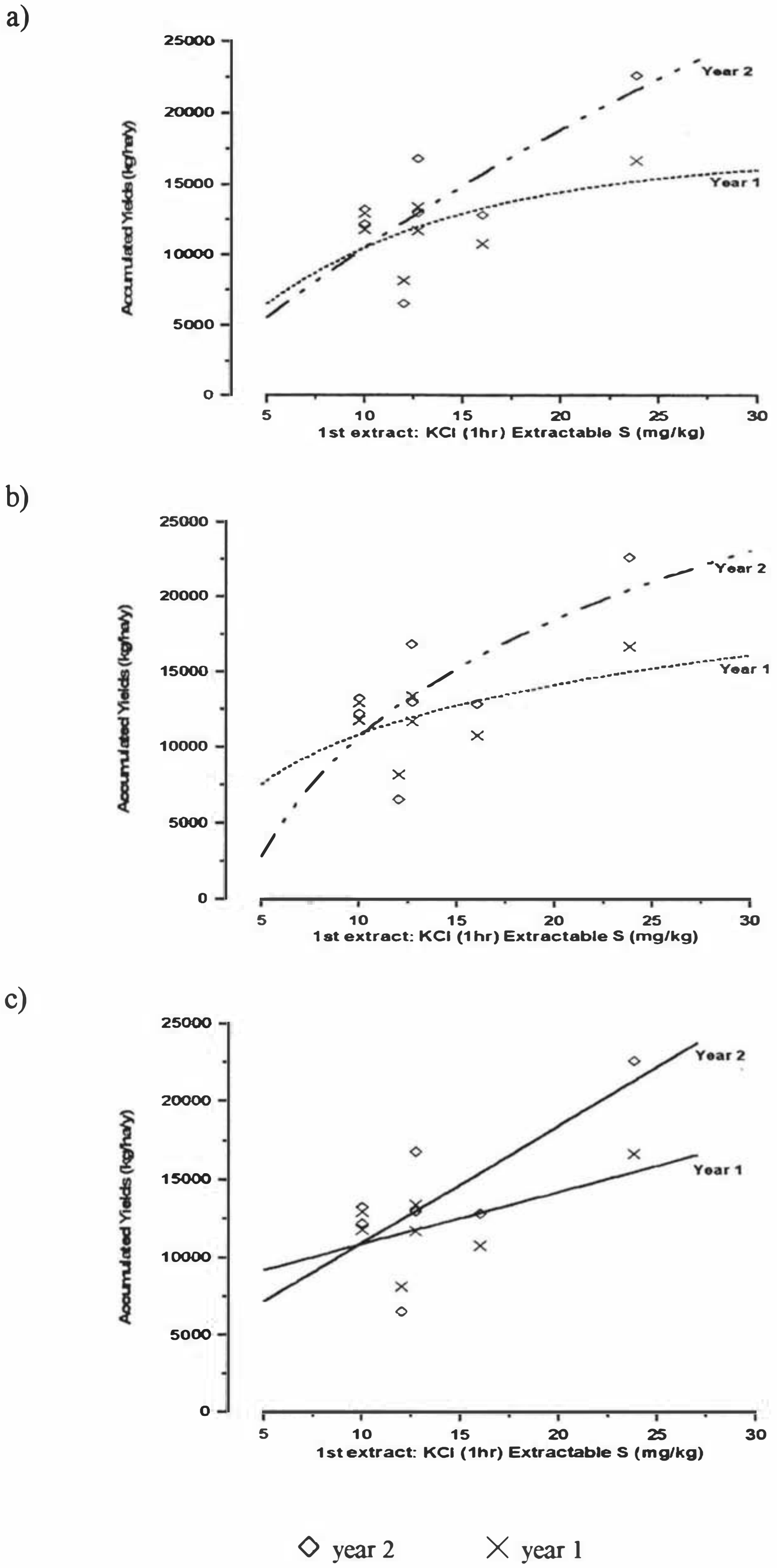


Figure 4.8 Regression analysis between annual accumulated yields and the amounts of S in the **first extract of sequential A method:KCl$_{(1hr\text{-}1stA)}$**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

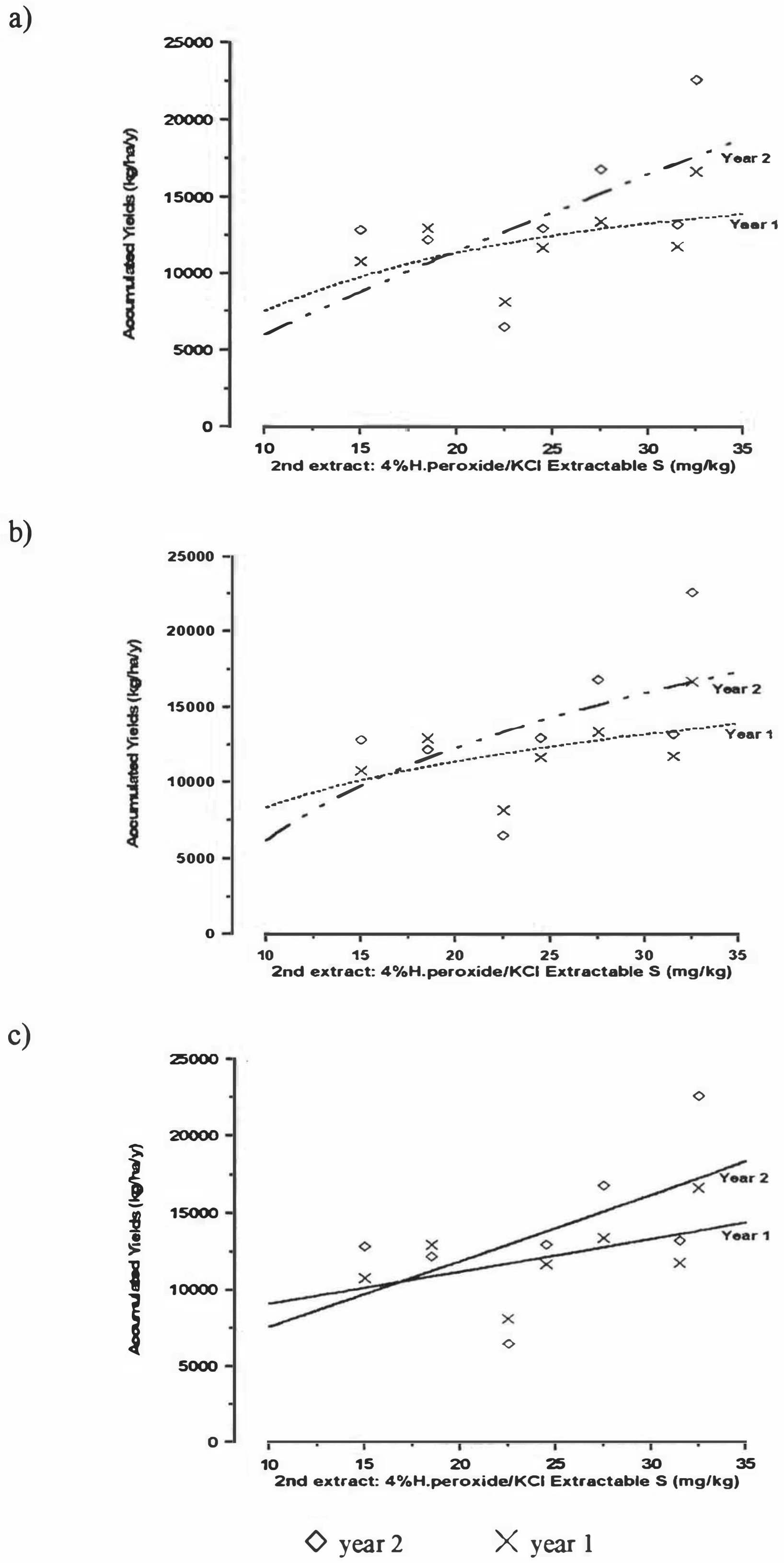


Figure 4.9 Regression analysis between annual accumulated yields and the amount of S in the **second extract of Sequential A method: 4% H_2O_2/KCl$_{(16hr\text{-}2ndA)}$**, using:

a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$
(See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

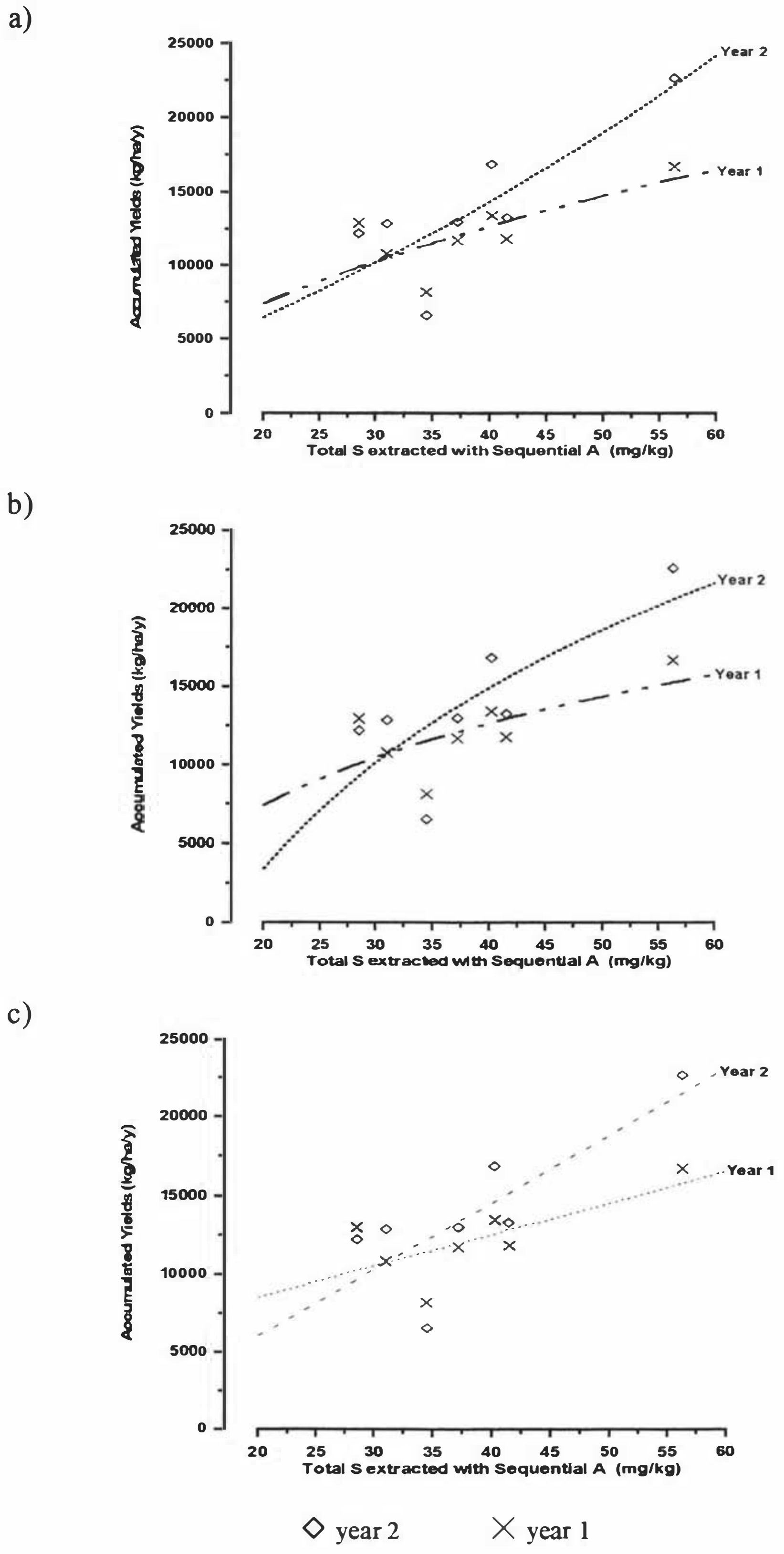


Figure 4.10 Regressions between annual accumulated yields and the **total amounts of S extracted in the Sequential A method: SeqA$_{(Tot-S)}$**, using:

a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$
(See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

Interestingly, the R^2 values for $SeqA_{(Tot\text{-}S)}$, were lower than $4\%H_2O_2/KCl_{(16hr)}$, the oxidation/extraction technique without pre-extraction (section 4.2.3.4), which also contains both **$Sul\text{-}S_{eqm}$** and **$Org\text{-}S_{labile}$**. These results is evident that improvements in soil tests that measures part of the soil organic S pool are related to the ratio of inorganic/organic S extracted rather than the specific extractant chemistry.

4.2.3.6 *Sequential B: $0.5\%H_2O_2/KCl_{(1hr\text{-}1stB)}$ followed by $4\%H_2O_2/KCl_{(24hr\text{-}2ndB)}$*

When using either the $KCl_{(16hr)}$ or the $4\%H_2O_2/KCl_{(16hr)}$ soil test values as indices of S availability, hence as indicators of pasture yield, more than 60% (R^2) of the variation in pasture yield could be explained by either test, using Equations 4.6 - 4.8. This was despite the two tests extracting different fractions of soil S, ie., 1.1 to 5.4% and 4.6 to 16.5% of total S respectively. These results prompted the need to investigate if greater extraction of soil organic S may improve the prediction of pasture yield, using a sequential extraction method, with greater extraction power (Sequential B method). The greater oxidising power is achieved by allowing a small volume of $4\%H_2O_2$ to contact the soil pellet for a longer period than the Sequential A method, prior to extraction.

Method

Duplicate two grams samples were pre-extracted with 40mls of a very mild concentration of hydrogen peroxide mixed with potassium chloride, $0.5\%H_2O_2/0.5M$ KCl, in 50ml centrifuge tubes for 1hr, on an end over end shaker. The mixture was centrifuged, decanted and analysed for S. To the residue, 5ml of $4\%H_2O_2$ were added and mixed well with a vortex mixer for 1min, then let stand for 24 hours. 35ml of 0.6M KCl were then added and shaken for 16hrs using an end over end shaker. (Note: The 0.6M KCl diluted to 0.5M when 35ml was made up to 40ml). The suspension was then centrifuged at 10000rpm for 10min, filtered through Whatman 42 filter paper and analysed for S as described above. The first and second extractants will be referred to as 0.5%H_2O_2/$KCl_{(1hr\text{-}1stB)}$ and 4%H_2O_2/$KCl_{(24hr\text{-}2ndB)}$ respectively, from here on. Their total will be referred to as $SeqB_{(Tot\text{-}S)}$ from here on.

Results and Discussion

The amounts of S extracted are given in Table 4.1. The first extractant, 0.5%H_2O_2/$KCl_{(1hr\text{-}1stB)}$, extracted more soil S (ranging from 1.8 to 5.3% of total soil S) than the $KCl_{(16hr)}$ extractant and less than the 4%H_2O_2/$KCl_{(16hr)}$ extractant as expected. The second extractant, 4%H_2O_2/$KCl_{(24hr\text{-}2ndB)}$, extracted the largest amounts of soil S (ranging from 3.6 to 18.7% of total soil S), which was consistent with the longer oxidation time. When the two extractants were added together, $SeqB_{(Tot\text{-}S)}$ contained soil S fractions that ranged from 5.4 to 24.0% of total soil S.

The R^2 values (Tables 4.2 - 4.4) shows that neither of these extractants performed as well as the Olsen P soil test in explaining the variation in annual accumulated yields on the unfertilised ontrol plots (Figs. 4.11a,b,c; 4.12a,b,c; and 4.13a,b,c). Therefore, it is likely that $SeqB_{(Tot\text{-}S)}$ is over-estimating the availability of the labile organic fraction, extracting some **Org-S$_{inert}$**, the soil S fraction that is not susceptible to microbial decomposition.

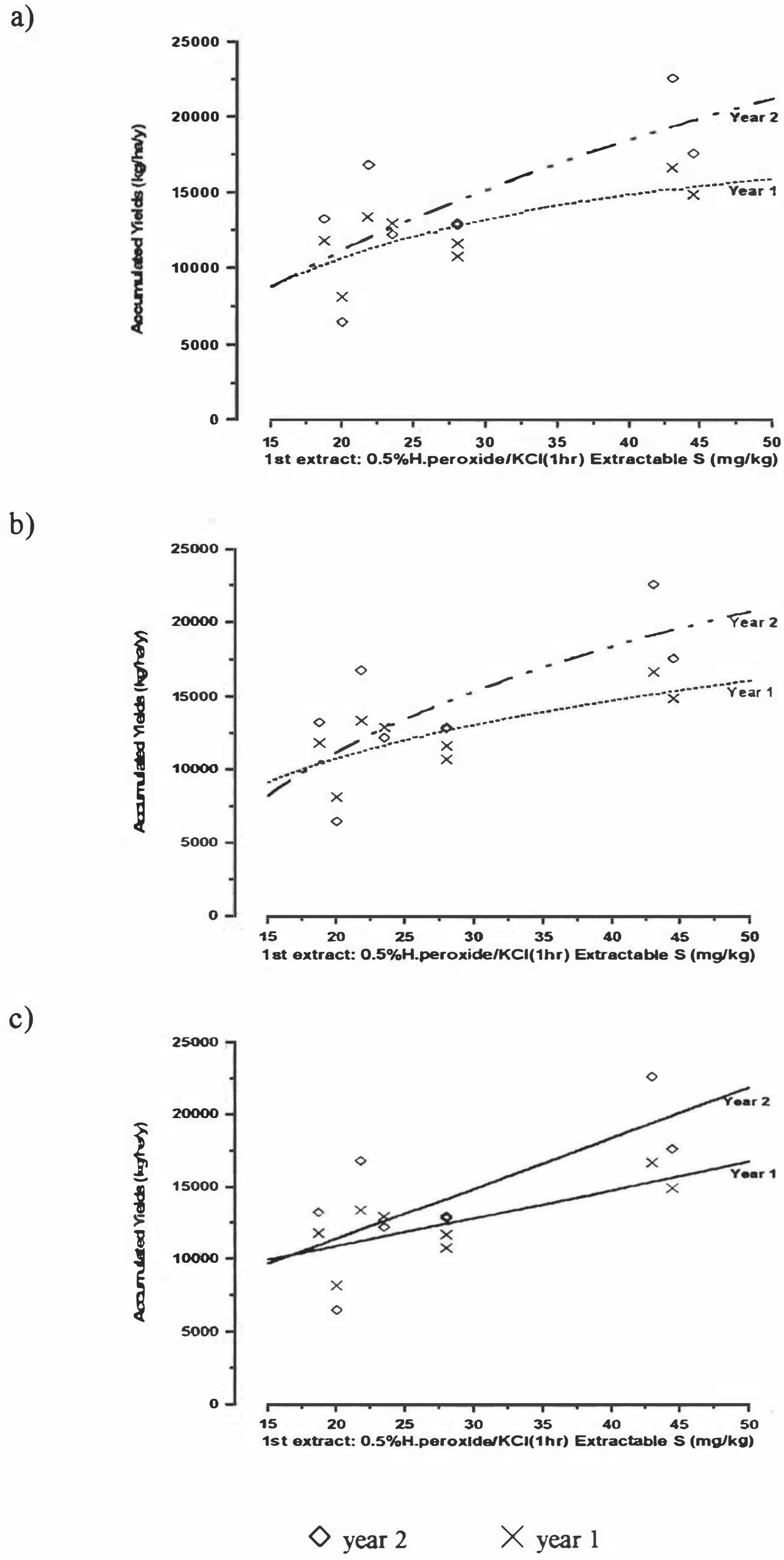


Figure 4.11 Regressions between annual accumulated yields and the amounts of S in the **first extract of sequential B method: 0.5% H_2O_2/KCl$_{(1hr\text{-}1stB)}$**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

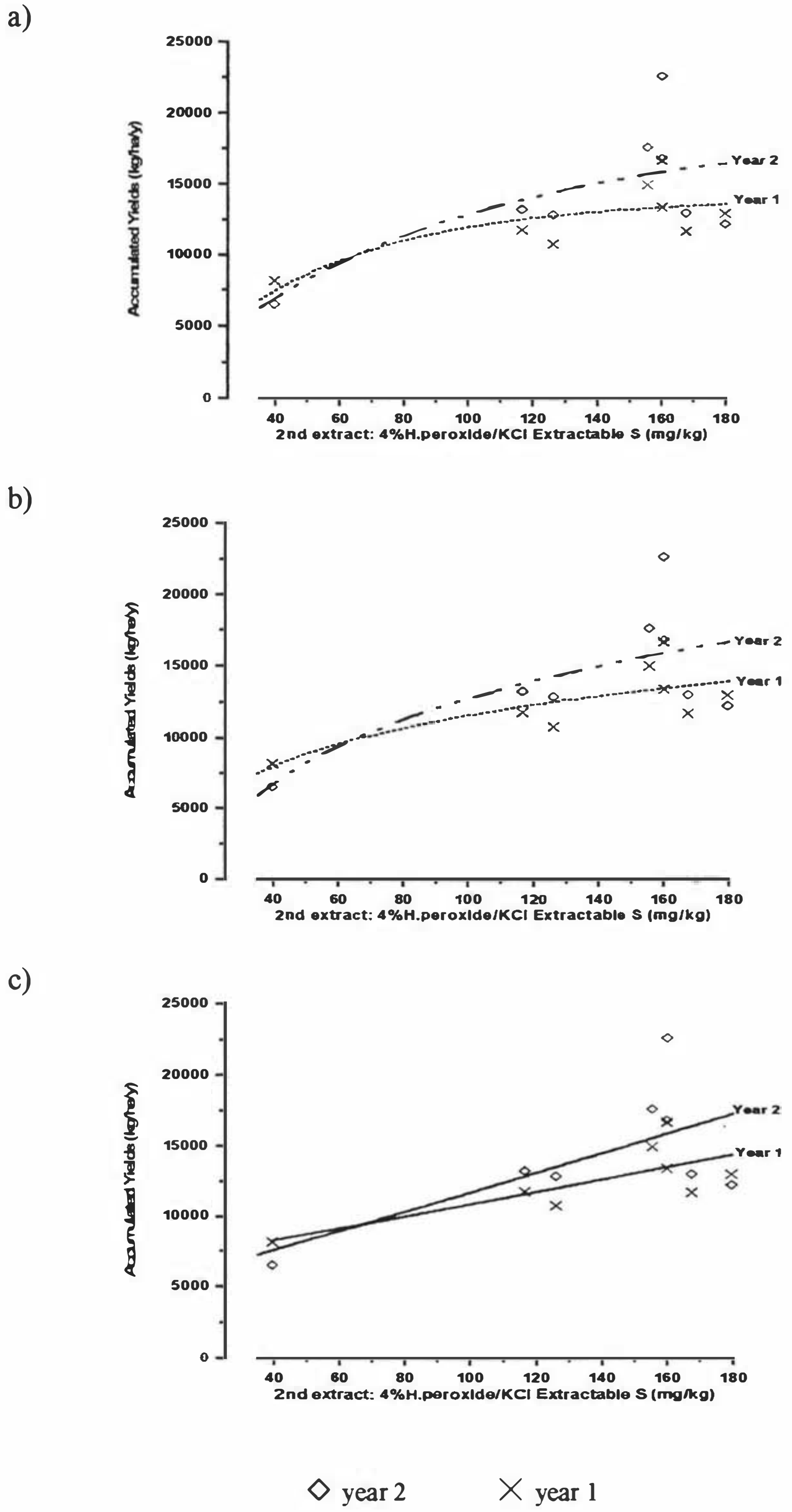


Figure 4.12 Regressions between annual accumulated yields and amounts of S in the **second extract of sequential B method: 4% $H_2O_2/KCl_{(24hr-2ndB)}$**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

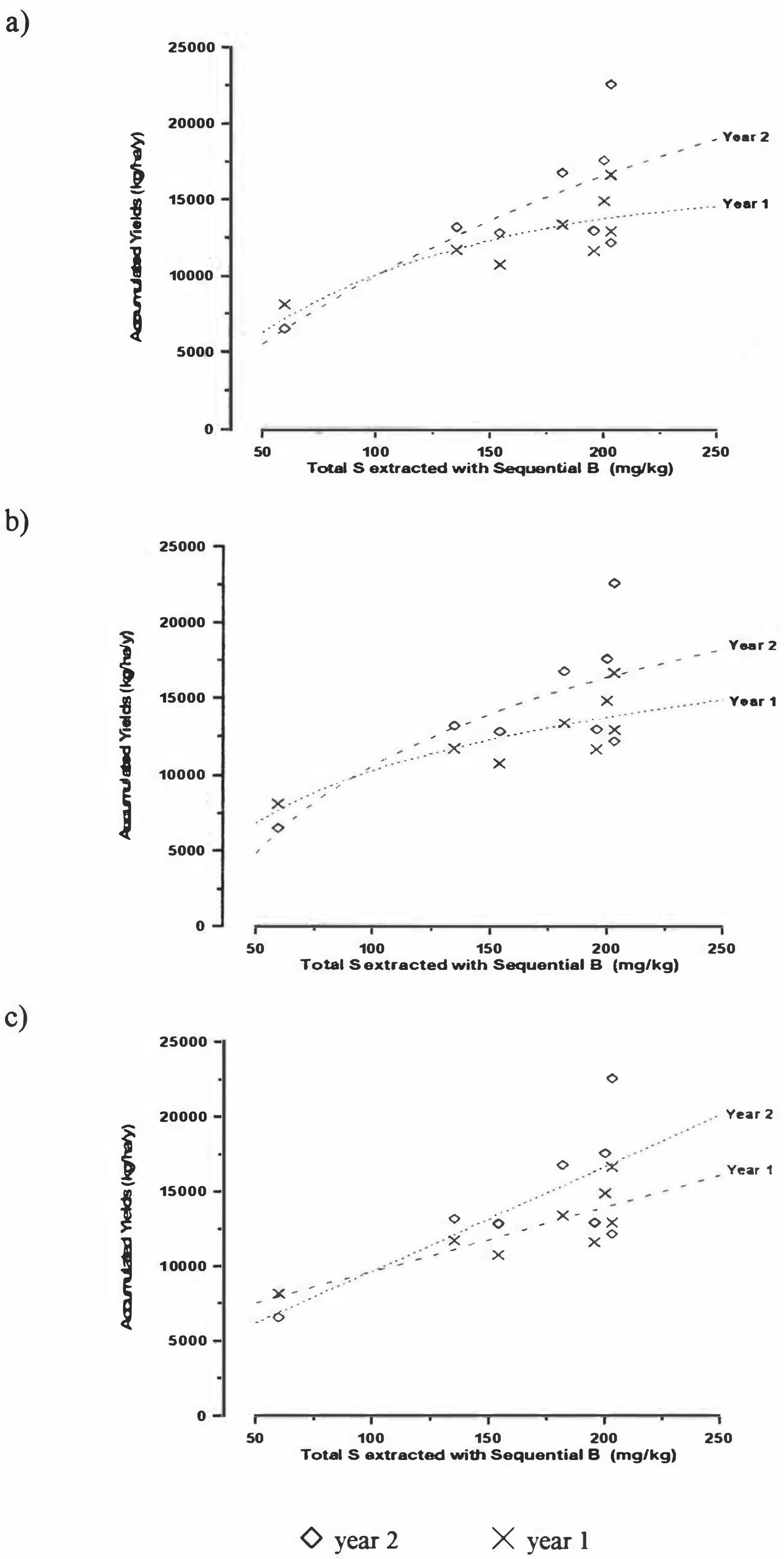


Figure 4.13 Regressions between annual accumulated yields and the **total amounts of S extracted with Sequential B method: SeqB$_{(Tot-S)}$**, using:

a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$
(See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

4.2.3.7 *MAF-SFS, Calcium phosphate extractable S:* $Ca\text{-}P_{(MAF\text{-}0.01M)}$,, $Ca\text{-}P_{(MAF\text{-}orgS)}$,, $Ca\text{-}P_{(MAF\text{-}TotS)}$

Subsequent to the soil S test research conducted in this thesis the New Zealand Ministry of Agriculture and Fisheries Soil Fertility Service [MAF SFS)] have conducted research to improve the diagnostic value of the standard extractable SO_4^2 test for pastures. In searching for a better soil test for S, MAF (SFS) developed new methods to improve the standard test of extracting soil sulphate S in 0.01M $Ca(H_2PO_4)_2$ at pH 4 and the analysis of sulphate S by autoanalysed turbidimetric measurement of $BaSO_4$ precipitation (Blakemore *et al.*, 1987). The improvements involved replacing the turbidimetric analysis with a more modern technique, based on High Performance Ion Chromatography (HPIC) and total S determination by inductively coupled plasma atomic absorption spectroscopy (ICP-AAS). The methods (described below) were suggested by Watkinson (1989) to be better because they remove analytical problems associated with high concentrations of phosphate and calcium, in traditional analysis by turbidimetric techniques. The amounts of organic S in the extract are calculated by subtracting sulphate S from total S (Watkinson and Kear, 1991). The amount of organic S purports to reflect the size of the mineralisable organic S pool in the soil. The soil samples from the Ballantrae trials were sent to the MAF-SFS Research Centre at Ruakura for extraction and analysis.

Methods
(As reported by Watkinson *et al.*, 1991, Pp.68)

Calcium phosphate extracts of soil

The air-dry soil samples, ground to <2mm, were extracted with 0.01M calcium phosphate, pH 4, at 1:5 (w/v) for 30min (SFS method). The suspensions were filtered through Whatman No.42 paper and samples of the filtrate were analysed for sulphate-S by HPIC and total S by inductively coupled plasma spectroscopy (ICP).

Sulphate-S in calcium phosphate extracts

Aliquots (20μl) of the filtered calcium phosphate extracts were analysed by HPIC using Shimadzu equipment comprising pump (LC-6A), autosampler (SIL-6A.SCL-6A), conductivity detector (CDD-6A) and oven, and integrator (C-R3A). The sulphate was separated from other ions using a Hamilton PRP-X100 anion-exchange column in a mobile phase of 0.05M phthalic acid adjusted to pH 4 with TRIZMA, at a flow rate of 1.5 ml/minute (Watkinson, 1989, Watkinson and Kear, 1991).

Total S in calcium phosphate extracts

The filtered extracts were analysed by ICAP using Labtest equipment. The 182.0nm line was measured to minimise calcium interference (Kear and Sutton, 1991).

Organic-S in calcium phosphate extracts

The organic-S in the extracts was calculated as the difference between the total S and the sulphate-S since no other inorganic species had been detected (Watkinson and Perrott, 1990).

Results and Discussion

The amounts of S extracted are given in Table 4.1. The amounts of sulphate-S in the extracts will be referred as Ca-P$_{(MAF-0.01M)}$, the organic-S as Ca-P$_{(MAF-OrgS)}$, and the total of these two extractants as Ca-P$_{(MAF-TotS)}$ from here on. The Ca-P$_{(MAF-0.01M)}$ extractable S varied from 8.3 to 18.0mg S/kg soil, while the Ca-P$_{(MAF-OrgS)}$ extractable S varied from 11.3 to 15.7mg S/kg soil. Calibration curves published by Watkinson and Kear (1995) would suggest that values of about 8mg/kg/soil or higher will return yields unlimited by S alone. All the soils in the 1990/1992-Ballantrae trials therefore, showed values of Ca-P$_{(MAF-OrgS)}$ extractable S that indicate soils non-responsive to applied S. However, the negative relationship between pasture yield and MAF-organic S has not been noted in Watkinson and Kear's study. This will be discussed further later.

The most surprising aspect of the results is that Ca-P$_{(MAF-0.01M)}$ did not correlate well with Ca-P$_{(0.04M)}$ (R^2 = 69%, Table 4.5), ie., the use of HPIC for analysis appears to generate results that are very different from the ones obtained using the modified method of Johnson and Nishita (1952), based on HI reduction and photometry. The biggest differences between the values of Ca-P$_{(\text{MAF-0.01M})}$ and Ca-P$_{(\text{0.04M})}$, were observed in the amounts extracted and analysed in the soils from sites located in the HF farmlets. The differences in the values obtained is believed to be caused by the Ca-P$_{(\text{0.04M})}$, analysed by photometry, containing some organic sulphate-esters that are reduced to H_2S by the hydriodic acid reducing mixture. Sakadevan (1991) also noted higher levels of organic ester S in the soils of HF farmlets than the LF farmlets. Ca-P$_{(\text{0.04M})}$ did correlate well with the other tests based on sulphate-S, like KCl$_{(\text{16hr})}$ and AER$_{(\text{Cl}^-)}$ (R^2 = 96 and 88% respectively), providing evidence that analysis by photometry using the modified method of Johnson and Nishita (1952) have been consistent. The HPIC method is therefore more precise in analysing for inorganic sulphates in the extracts, but appears not to differentiate between the soils with different fertiliser history.

Compared to SeqA$_{(\text{Tot-S})}$ and SeqB$_{(\text{Tot-S})}$, no improvement was gained when Ca-P$_{(\text{MAF-0.01M})}$ (Figs. 4.14a,b,c) and Ca-P$_{(\text{MAF-OrgS})}$ (Figs. 4.15a,b,c) were summed as Ca-P$_{(\text{MAF-TotS})}$ (Figs. 4.16a,b,c) and used to explain the variation in pasture yields, using Equations 4.6 - 4.8 (Tables 4.2 - 4.4). Interestingly, there was a negative trend in the relationship between actual yield and Ca-P$_{(\text{MAF-OrgS})}$ (Figs. 4.15a,b,c) similar to the relationship using total S (Fig. 3.3). Figures 4.15a,b,c appears to reflect the declining total soil organic S (**Org-S$_{labile}$ + Org-S$_{inert}$**) at the HF sites, but not annual accumulated yields. It indicates that as the rate of mineralisation is faster at the HF farmlet sites (Sakadevan, 1991), the **Org-S$_{inert}$** is reduced reflecting the leaky nature of the HF sites, while **Org-S$_{labile}$** remains at an approximate steady-state (Equation 4.3). As suggested by Equations 4.4 and 4.5, **Org-S$_{inert}$** does not affect the level of plant available S, **Sul-S$_{eqm}$**, hence, it have no direct effect on pasture yield.

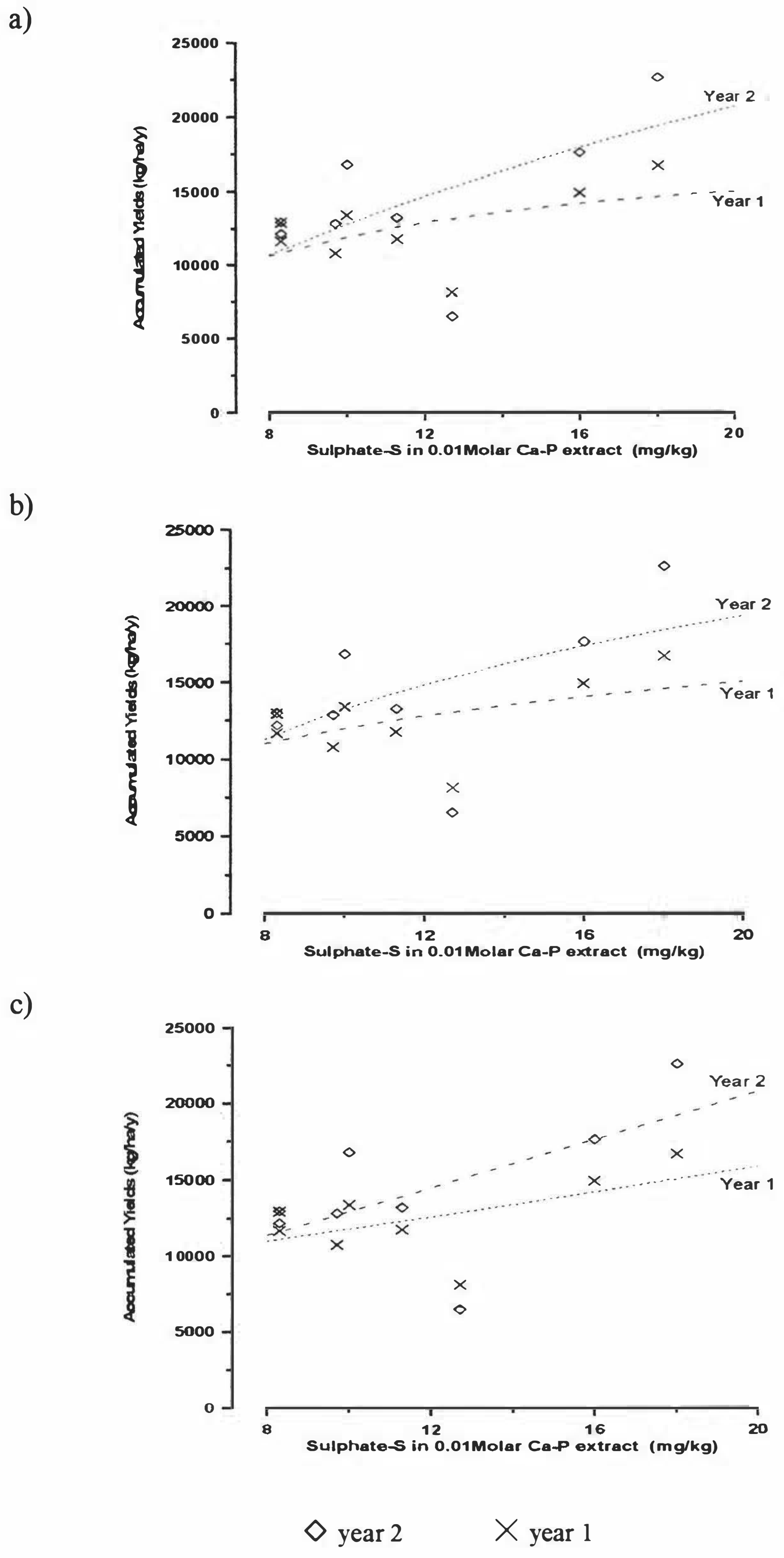


Figure 4.14 Regressions between annual accumulated yields and **sulphate-S in 0.01M Ca(H_2PO_4)$_2$ extract: Ca-P$_{(MAF\text{-}0.01M)}$**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

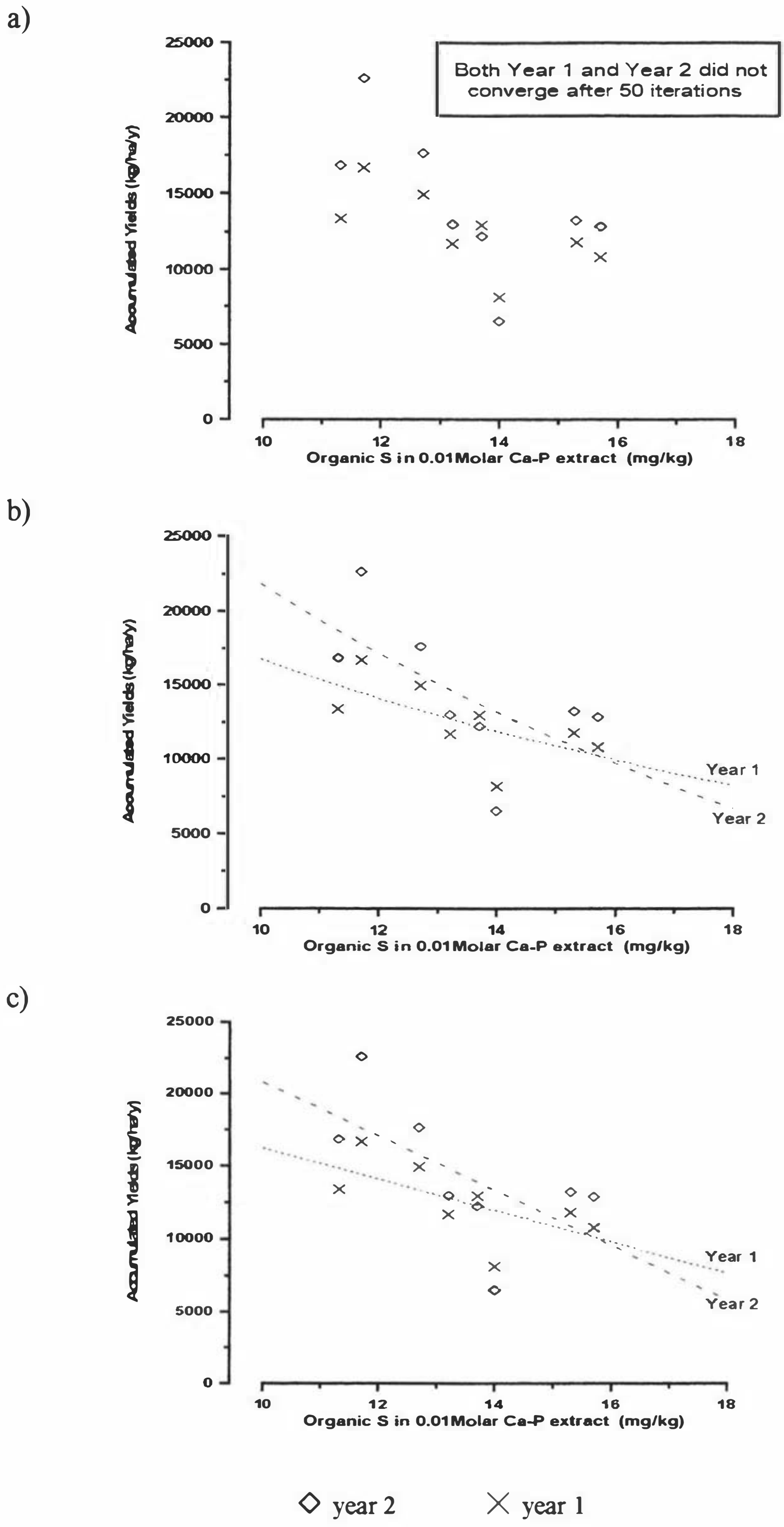


Figure 4.15 Regressions between annual accumulated yields and **organic S in 0.01M $Ca(H_2PO_4)_2$ extract: Ca-$P_{(MAF\text{-}org\text{-}S)}$**, using:

a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$
(See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

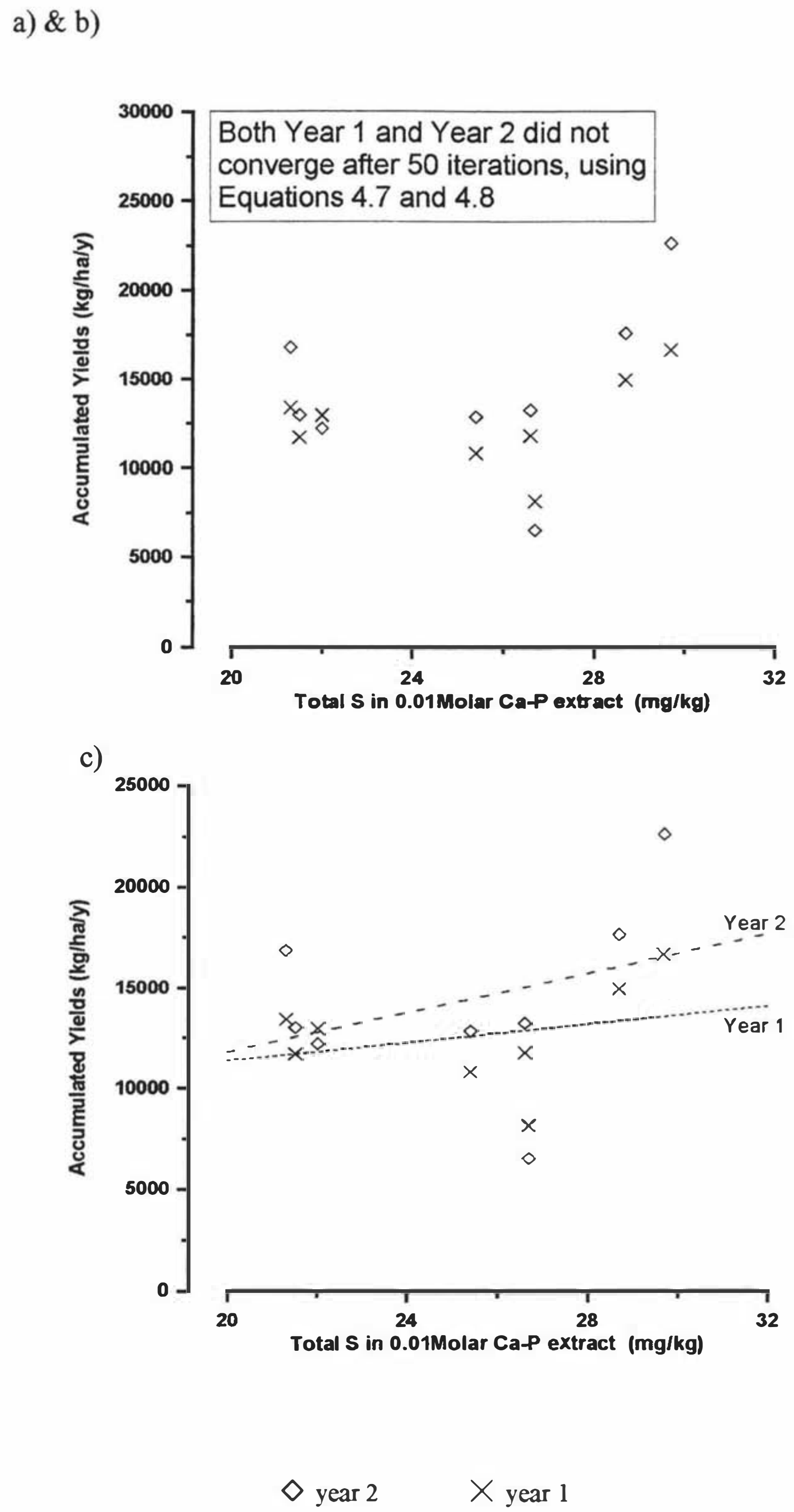


Figure 4.16 Regression analysis between annual accumulated yields and **total amounts of S extracted with 0.01M Ca-P: Ca-P$_{(MAF\text{-}TotS)}$**, using:

a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$
(See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

The Ca-$P_{(MAF\text{-}OrgS)}$ test therefore, apears to reflect the total organic S (**Org-S_{labile}** + **Org-S_{inert}**) rather than **Org-S_{labile}** only, which is the fraction regulating the rate of S mineralisation, hence, S availability. This being so, Ca-$P_{(MAF\text{-}OrgS)}$ cannot be used for further development of farm management diagnostic tools, beyond these soil test models. Thus, the negative relationship between pasture yield and Ca-$P_{(MAF\text{-}OrgS)}$ would be redundant. This finding is contrary to the results published by Watkinson (1994), which showed a positive relationship between the pasture growth response to S fertiliser. The results reported by Watkinson and Kear (1995) showed only a few data points above 11mg S/kg soil. Watkinson and Kear moved away from the calcium phosphate extractions and suggested that potassium phosphate was a better extractant. While they suggested that analytical interferences due to Ca^{2+} was the main reason for the calcium extractants not working (in contrast to Watkinson (1994)), it is suggested here that the approach of subtracting Ca-$P_{(MAF\text{-}0.0M)}$ from Ca-$P_{(MAF\text{-}TotS)}$ to obtain Ca-$P_{(MAF\text{-}OrgS)}$ is also very questionable because there eis no way of finding out if Ca-$P_{(MAF\text{-}OrgS)}$ was also extracting **Org-S_{inert}**. It is therefore not surprising that the patterns of the dependency of pasture yields on Ca-$P_{(MAF\text{-}OrgS)}$ reflects soil total S for these trials (see Fig. 3.3.

4.2.3.8 *Olsen P soil test*

Saunders (1987) commented that from his experience, the Olsen P soil test is the most reliable measure of a pastures responsiveness to applied P, for a wide range of soils under pasture. However, several other studies showed that when insoluble or partially soluble sources of P are applied, the Olsen P soil test does not seem to be successful in the assessment of available P (eg., Cornforth *et al.*, 1983; Mackay *et al.*, 1984; Saggar *et al.*, 1993). At Ballantrae, neither insoluble nor partially soluble sources of P have been applied in the past.

Method

Duplicate one gram air-dried soil samples were weighed into 50ml centrifuge tubes, 20ml of 0.5M $NaHCO_3$ solution at pH 8.5 were added and the tubes shaken on an end over end shaker for 30min. The mixture was then centrifuged at 10000rpm for 10min, filtered through Whatman No.42 filter paper. The phosphorus extracted was analysed by the method of Murphy and Riley (1962).

Results and Discussion

The amounts of P extracted are given in Table 4.1. The Olsen P soil test measures "plant available" inorganic P extracted by the 0.5M $NaHCO_3$ solution. As expected, there was less plant available P in the soils from the medium slope sites than in the soils from the low slope sites, except for the sites located on the LFNF farmlet where the low slope site is more exposed to the prevailing winds. Interestingly, the HFNF sites showed values that are slightly higher than the LFLF sites, indicating the residual value of SSP fertilisers applied ten years earlier at a rate of 576kg SSP/ha/yr, over five years, compared to the slow buildup of fertility due to continuous applications of 125kg SSP/ha/yr over fifteen years.

When regressed against annual accumulated yields on the control plots (Fig. 4.17), the values of the coefficients of determination (R^2) were similar to those obtained using the 4%H_2O_2/$KCl_{(16hr)}$ and the $KCl_{(16hr)}$ soil tests (Tables 4.2 - 4.4). It also correlated well with these two tests for S availability (Table 4.5). However, the patterns of S availability in the HFNF farmlets compared to the LFLF farmlets using the 4%H_2O_2/$KCl_{(16hr)}$ soil test appears to resemble the patterns observed with the Olsen P test better than if the $KCl_{(16hr)}$ soil test is used the index of S availability (Table 4.1).

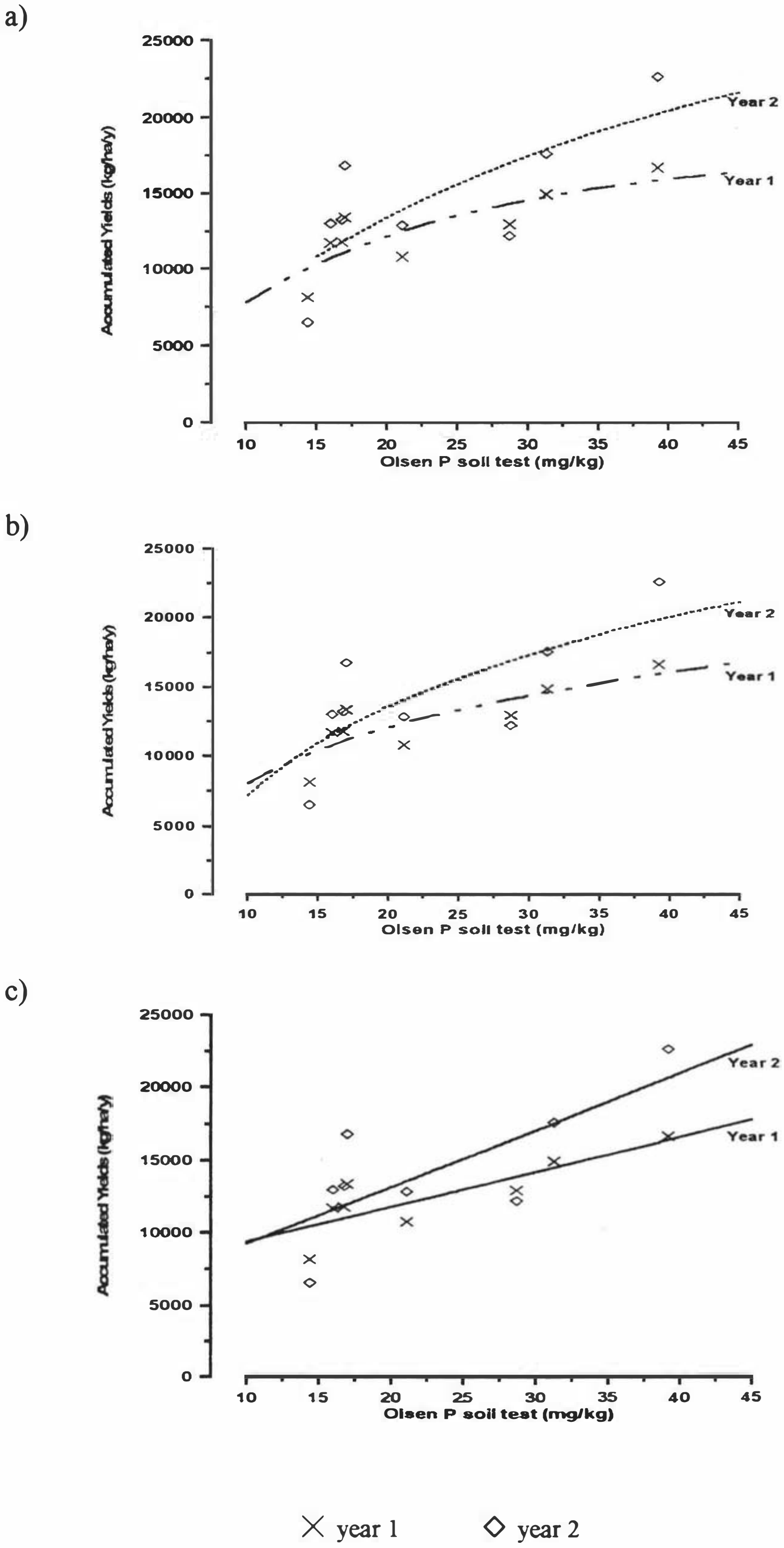


Figure 4.17 Regressions between annual accumulated yields and **Olsen P soil test**, using: a) $y = a(1 - e^{bx})$; b) $y = a + b\ln x$; and c) $y = a + bx$ (See Tables 4.2, 4.3, and 4.4 for parameters and R^2 values)

Table 4.1 Amounts of S* in each extractant ranked for an index of S availability

SOIL TEST	**TRIAL SITE**							
	LFNFL	LFNFM	LFLFL	LFLFM	HFNFL	HFNFM	HFHFL	HFHFM
Ca-P$_{(0.04M)}$	9.7	8.0	13.2	15.0	11.2	8.3	35.3	31.5
$KCl_{(16hr)}$	12.5	13.0	17.3	19.3	16.0	15.2	30.7	26.0
AER$_{(Cl^-)}$	14.7	14.0	17.8	14.9	12.2	12.0	25.8	-
4%$H_2O_2/KCl_{(16hr)}$	50.7	61.3	82.7	61.3	82.7	77.3	105.3	80.0
$KCl_{(1hr\text{-}1stA)}$	12.0	10.0	16.0	12.7	10.0	12.7	23.8	-
4%$H_2O_2/KCl_{(16hr\text{-}2ndA)}$	22.5	31.5	15.0	24.5	18.5	27.5	32.5	-
SeqA$_{(Tot\text{-}S)}$	34.5	41.5	31.0	37.2	28.5	40.2	56.3	-
0.5% $H_2O_2/KCl_{(1hr\text{-}1stB)}$	20.0	18.7	28.0	28.0	23.5	21.8	43.0	44.5
4% $H_2O_2/KCl_{(24hr\text{-}2ndB)}$	39.5	116.5	126.0	167.5	179.5	160.0	160.0	155.5
SeqB$_{(Tot\text{-}S)}$	59.5	135.2	154.0	195.5	203.0	181.8	203.0	200.0
CaP$_{(MAF\text{-}0.01M)}$	12.7	11.3	9.7	8.3	8.3	10.0	18.0	16.0
CaP$_{(MAF\text{-}Org\text{-}S)}$	14.0	15.3	15.7	13.2	13.7	11.3	11.7	12.7
CaP$_{(MAF\text{-}Tot\text{-}S)}$	26.7	26.6	25.4	21.5	22.0	21.3	29.7	28.7
Olsen P	14.4	16.8	21.1	16.0	28.7	17.0	39.2	31.3

* units: mg S/kg soil

Table 4.2 Parameter values and coefficient of determination values (R^2) from regression analysis, using the mathematical expression: $y = \mathbf{a}(1 - e^{\mathbf{b}x})$

Chemical Extractant (*Soil Test*)	**Year 1** April 1990-May 1991			**Year 2** May 1991-June 1992		
	a	**b**	**adj. R^2(%)**	**a**	**b**	**adj. R^2(%)**
Ca-P$_{(0.04M)}$	15302	-0.1361	23.6	20869	-0.0852	31.4
KCl$_{(16hr)}$	19337	-0.0588	61.2	48871	-0.0189	62.7
AER$_{(Cl^-)}$	16854	-0.0842	2.1	73015	-0.0133	26.1
4%H_2O_2/KCl$_{(16hr)}$	30688	-0.0071	64.0	30441	-0.0051	64.1
KCl$_{(1hr\text{-}1stA)}$	16938	-0.0969	10.6	52069	-0.0226	43.0
4%H_2O_2/KCl$_{(16hr\text{-}2ndA)}$	15343	-0.0678	3.9	68466	-0.0092	16.0
SeqA$_{(Tot\text{-}S)}$	23270	-0.0165	32.6	27323	-0.0106	57.5
0.5% H_2O_2/KCl$_{(1hr\text{-}1stB)}$	17784	-0.0458	44.1	33262	-0.0206	45.8
4% H_2O_2/KCl$_{(24hr\text{-}2ndB)}$	14079	-0.0193	45.9	18759	-0.0116	39.4
SeqB$_{(Tot\text{-}S)}$	15890	-0.0101	55.6	29271	-0.0042	47.4
CaP$_{(MAF\text{-}0.01M)}$	16021	-0.1371	4.3	32994	-0.0492	17.9
CaP$_{(MAF\text{-}Org\text{-}S)}$	-	-	no fit	-	-	no fit
CaP$_{(MAF\text{-}Tot\text{-}S)}$	-	-	no fit	-	-	no fit
Olsen P	17644	-0.0584	60.8	28271	-0.0321	44.3

Table 4.3 Parameter values and coefficient of determination values (R^2) for the regression analysis, using the mathematical expression: $y = \mathbf{a} + \mathbf{b}\ln x$

Chemical Extractant (*Soil Test*)	**Year 1** April 1990-May 1991			**Year 2** May 1991-June 1992		
	a	**b**	**adj. R^2** (%)	**a**	**b**	**adj. R^2** (%)
Ca-P$_{(0.04M)}$	4097	3195	40.7	-627	5663	38.1
KCl$_{(16hr)}$	-6856	6730	62.0	-20824	12201	61.9
AER$_{(Cl^-)}$	-130	4514	4.8	-15361	10701	19.6
4%H_2O_2/KCl$_{(16hr)}$	-28040	9448	64.5	-58718	17010	63.3
KCl$_{(1hr\text{-}1stA)}$	-180	4790	16.9	-15350	11304	38.5
4%H_2O_2/KCl$_{(16hr\text{-}2ndA)}$	-1934	4465	7.8	-14345	8914	11.5
SeqA$_{(Tot\text{-}S)}$	-15318	7591	30.4	-46419	16630	48.7
0.5% H_2O_2/KCl$_{(1hr\text{-}1stB)}$	-6528	5787	45.7	-19992	10419	44.7
4% H_2O_2/KCl$_{(24hr\text{-}2ndB)}$	-6579	3948	48.9	-17495	6574	38.6
SeqB$_{(Tot\text{-}S)}$	12673	4992	58.2	-27826	8349	47.0
CaP$_{(MAF\text{-}0.01M)}$	1898	4387	10.7	-6930	8767	16.6
CaP$_{(MAF\text{-}Org\text{-}S)}$	50150	-14498	32.6	81432	-25862	31.0
CaP$_{(MAF\text{-}Tot\text{-}S)}$	-	-	no fit	-	-	no fit
Olsen P	-5397	5836	62.6	-14291	9316	44.7

Table 4.4 Parameter values and coefficient of determination values (R^2) for the regression analysis, using the mathematical expression: $y = \mathbf{a} + \mathbf{b}x$

Chemical Extractant *(Soil Test)*	**Year 1** April 1990-May 1991			**Year 2** May 1991-June 1992		
	a	**b**	**R^2 (%)**	**a**	**b**	**R^2 (%)**
Ca-P$_{(0.04M)}$	9520	184	57.2	8926	330	55.9
KCl$_{(16hr)}$	6309	333	67.7	2969	608	68.6
AER$_{(Cl^-)}$	7510	296	29.0	3385	661	41.3
4%H_2O_2/KCl$_{(16hr)}$	3020	127	68.8	-2966	231	69.1
KCl$_{(1hr\text{-}1stA)}$	7536	337	38.6	3445	753	54.8
4%H_2O_2/KCl$_{(16hr\text{-}2ndA)}$	6995	213	27.8	3305	431	32.5
SeqA$_{(Tot\text{-}S)}$	4523	200	49.0	-2449	425	63.0
0.5% H_2O_2/KCl$_{(1hr\text{-}1stB)}$	7038	194	55.8	4474	348	54.6
4% H_2O_2/KCl$_{(24hr\text{-}2ndB)}$	6564	43	56.2	4851	69	43.1
SeqB$_{(Tot\text{-}S)}$	5380	43	68.2	2702	70	54.8
CaP$_{(MAF\text{-}0.01M)}$	7828	401	30.2	5194	779	34.6
CaP$_{(MAF\text{-}Org\text{-}S)}$	26939	-1069	41.3	39577	-1874	38.5
CaP$_{(MAF\text{-}Tot\text{-}S)}$	6748	230	8.5	1946	492	11.8
Olsen P	7006	241	68.8	5358	391	55.1

Table 4.5 Correlation coefficients between soil tests

	Soil Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Ca-P$_{(0.04M)}$	1	1.00													
KCl$_{(16hr)}$	2	0.96	1.00												
AER$_{(CT)}$	3	0.88	0.79	1.00											
4%H$_2$O$_2$/KCl$_{(16hr)}$	4	0.45	0.57	0.44	1.00										
KCl$_{(1hr-1stA)}$	5	0.87	0.84	0.92	0.57	1.00									
4%H$_2$O$_2$/KCl$_{(16hr-2ndA)}$	6	0.16	0.13	0.11	0.01	0.09	1.00								
SeqA$_{(Tot-S)}$	7	0.58	0.55	0.54	0.23	0.54	0.75	1.00							
0.5%H$_2$O$_2$/KCl$_{(1hr-1stB)}$	8	0.84	0.93	0.84	0.46	0.88	0.06	0.45	1.00						
4%H$_2$O$_2$/KCl$_{(24hr-2ndB)}$	9	0.01	0.23	0.01	0.38	0.03	0.01	0.02	0.17	1.00					
SeqB$_{(Tot-S)}$	10	0.25	0.39	0.04	0.48	0.10	0.01	0.06	0.32	0.97	1.00				
CaP$_{(0.01M)}$	11	0.69	0.55	0.69	0.09	0.62	0.37	0.71	0.36	0.11	0.01	1.00			
CaP$_{(MAF\ OrgS)}$	12	0.21	0.27	0.04	0.17	0.16	0.24	0.31	0.19	0.19	0.23	0.81	1.00		
CaP$_{(MAF\ TotS)}$	13	0.47	0.36	0.60	0.29	0.39	0.15	0.37	0.55	0.01	0.33	0.15	0.39	1.00	
Olsen P	14	0.73	0.74	0.53	0.77	0.53	0.04	0.28	0.53	0.25	0.37	0.45	0.16	0.29	1.00

4.3 GENERAL DISCUSSION

When all the soil tests, investigated as potential indices of S availability, were used for regression analysis against annual pasture yield on the unfertilised control plots, using the mathematical Equations 4.6 - 4.8, the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test performed the best (R^2 ranging from 63 - 69%), followed by $KCl_{(16hr)}$ (R^2 ranging from 61 - 69%), then $SeqB_{(Tot\text{-}S)}$ (R^2 ranging from 47 - 68%). The rest of the soil S tests investigated showed R^2 values that were generally below 50% (Tables 4.2 - 4.4).

An interesting feature of these results is that the $4\%H_2O_2/KCl_{(16hr)}$ and the $KCl_{(16hr)}$ soil tests showed similar values of the coefficients of determination (R^2) for all mathematical equations used (Eqns. 4.6 - 4.8), despite the two tests extracting different fractions of total S, ie. ranges of S extracted in each test were 4.6 - 14.1% and 1.1 - 4.1% of total S respectively. The amounts of S extracted in the $4\%H_2O_2/KCl_{(16hr)}$ extractant were about 4 - 5 times more than the amounts extracted in $KCl_{(16hr)}$. The results from this study suggests that the chemistry of the extractants is not as important as the $\text{Org-S}_{labile}/\text{Sul-S}_{eqm}$ ratio extracted, as implied by Equations 4.4 and 4.5.

The $4\%H_2O_2/KCl_{(16hr)}$ was only slightly better correlated with the Olsen P soil test than the $KCl_{(16hr)}$ soil tests. The Olsen P test which also showed similar R^2 values to these soil S tests, when regressed against annual accumulated yields on the unfertilised control plots (Tables 4.2 - 4.4). The $4\%H_2O_2/KCl_{(16hr)}$ however showed a much better spread of the data than the $KCl_{(16hr)}$. It therefore appears, that $4\%H_2O_2/KCl_{(16hr)}$ test reflects the ability of the soil to supply the effective quantities of S that are used to utilise available P, as measured by the Olsen P test. The strong correlation between this soil test and Olsen P, seems to suggest that pasture growth is influenced more by the interaction of S and P, rather than each nutrient alone, i.e., S and P as growth factors are not exclusive of each other.

It can be concluded that the lack of response to the +S treatment in Chapter Three, indicates that there is adequate soil S at Ballantrae at all sites to fully utilise soil P. On the other hand, soil S supplies at some LF sites, were not adequate to also utilise applied fertiliser P, as indicated by their responsiveness to the +SP treatment. These effects of soil S and P availabilities, influencing pasture response to S and P fertiliser applications, are investigated in the next chapter, using relative yield as the pasture yield parameter.

CHAPTER FIVE

THE ABILITY OF SOIL SULPHUR AND PHOSPHORUS TESTS TO PREDICT PASTURE RESPONSES TO APPLIED FERTILISERS

5.1 INTRODUCTION

Conventionally, the widespread responses to SSP fertiliser in New Zealand pastures have been attributed primarily to the P it contain while any S deficiency that may have existed would have been eliminated by the use of this fertiliser. Accordingly, the Olsen P test has been the most commonly used soil test to predict pasture responses to SSP fertiliser.

In the previous chapter, it was found that the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test was not only as good at predicting annual accumulated yields on the unfertilised control plots as the Olsen P test (Tables 4.2-4.4), but was also strongly correlated with the Olsen P test (Table 4.5). This shows that the increase of soil P status using SSP fertiliser (measured as Olsen P) has a marked impact on the build up of soil organic S as suggested by Walker *et al.* (1959) and provides evidence that the $4\%H_2O_2/KCl_{(16hr)}$ test is adequate to represent the ability of the soil to supply plant available S, ie. an index of S availability. Furthermore, it can be concluded that the $4\%H_2O_2/KCl_{(16hr)}$ test has the potential as a general index of soil fertility on pastures previously fertilised with SSP as an alternative to the Olsen P test.

In Chapter Three, it was shown that there were no significant differences in the increase of total pasture yields due to application of S alone (+S treatment), from those of the unfertilised control plots at all sites (Table 3.3). Therefore, it is not possible to prove that the relationships between actual yields on the unfertilised control plots and the

$4\%H_2O_2/KCl_{(16hr)}$ test (Fig. 4.7) were caused by S limitation of pasture growth. As suggested in the conceptual model in section 3.4.1, S deficiency should be defined only on the basis of whether there is adequate soil S supply to utilise soil and fertiliser P rather than on the S required by grass to assimilate N in protein synthesis. From this perspective, it can be concluded that i) the lack of response to the +S treatment was an indication that there was adequate soil S supply to efficiently utilise soil P at all sites, and ii) as the build up of soil organic S has been influenced by soil P status (Walker *et al.*, 1959; Nguyen and Goh, 1990; Sakadevan *et al.*, 1993), the lower actual yields on the unfertilised control plots with lower $4\%H_2O_2/KCl_{(16hr)}$ test values (Fig. 4.7), are likely caused by the associated lower soil P status, mainly on the LF areas or medium slope (M) sites.

When S and P fertilisers were applied together (+SP treatment, equivalent to SSP fertilisation), there were significant increases in total pasture yields on three of the four LF sites. This indicates that there was adequate soil S to utilise soil P at all sites, but not adequate at the LF sites to also utilise fertiliser P. While conventional reasoning would attribute the responses to the +SP treatment to P, the conceptual model in section 3.4.1 implies that application of P may induce S deficiencies in some soils. In these situations, the Olsen P test would not have the ability to assess if the P applied in SSP would be utilised or not and also if the applied P induced an S deficiency or not. On the other hand, if the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test is a reliable index of S availability, then it should be able to predict both the efficiency of utilising applied P and an induced S deficiency if there was any.

The first objective of this chapter therefore, is to compare the relative strengths of the extractants $4\%H_2O_2/KCl_{(16hr)}$ and Olsen P as indicators of pasture responsiveness to application of S and P fertilisers together (+SP treatment), ie., using RY (see section 5.2.1), the relative yield calculated from the yields on the +SP plots of the 1990/1992-Ballantrae Trials, as the pasture yield parameter.

Colwell *et al.* (1988) were strongly critical of the RY approach because it is obvious that the yields associated with a given value on the *x*-axis (soil test value) are not simply proportional to a single, corresponding **a** value (Eqns. 4.6 and 4.7 in previous chapter) or maximum yield. Hence, RY has limited value as a diagnostic tool in farm management because it cannot provide the basis for estimating fertiliser rates as farmers must justify their expenditures for fertilisers on the basis of actual increase in yields. The use of RY as the pasture yield parameter in this thesis is therefore, purely for research purposes to study the interaction of S and P in regulating the N economy of legume\grass mixed swards, rather than as a diagnostic tool.

It was discussed in the conceptual model in section 3.4.1 that the promotion of legume growth and N_2 fixation by S and P nutrients is very much influenced by the amounts of inorganic soil N. The second objective of this chapter is to investigate the influence of N fertiliser application on pasture responsiveness to S.

The two objectives of this chapter are investigated using the 1990/1992-Ballantrae Trials data presented in Chapter Three and data from a wider range of trial sites on different soil types (section 5.4).

5.2 METHODS

5.2.1 Relative Yield as the Pasture Yield Parameter

The device commonly used to normalise pasture yield data from different field trials into a unified framework is called *relative yield* (RY), calculated as the percentage increase in yield due to application of the nutrient in question as fertiliser, ie.,

$$RY = \frac{\text{Yield (Nutrient not applied)}}{\text{Yield (Nutrient applied)}} \times \frac{100}{1} \quad \text{.} \qquad \text{Equation 5.1}$$

A calibration curve is then provided by regression between RY and the mean soil test value of the plots where the nutrient in question was not applied. In general, a soil test value above which the RY value of 90% is obtained, is chosen as the target value (Hedley *et al.*, 1995) to be achieved through fertiliser application.

The Yield(Nutrient not applied) is commonly referred to as the control yield, while the Yield(Nutrient applied) is commonly referred to as the maximum yield. The use of the above notation is because, there are several ways of estimating RY with respect to the nutrient under investigation as a growth factor, in the presence of others. For example, to study P as a growth factor, RY can be estimated as either, i) the percentage increase in yield on a +P fertilised plot above the yield on a control plot where no fertiliser was applied, or ii) the percentage increase in yield on a +SP fertilised plot above the yield on a +S fertilised plot, ie., response to P in the presence of a basal application of S.

Often, not enough attention is paid to the effects of combined nutrients applied in fertilisers, when discussing the response to a certain nutrient. For example, Morton *et al.* (1995) reported a whole series of trials to estimate P response data used in the AgResearch 'Outlook' P model (Metherell *et al.*, 1995). The P responses in some cases were estimated using P applied as SSP fertiliser. The calibrations between these yield data and Olsen P, used in the AgResearch 'Outlook' P model has to be questionable because there was no recognition of the interaction of P with the S applied. In contrast, this thesis pays close attention to this interaction. The fertiliser treatments included in the design of field experiments for calculations of RY, are therefore considered as an integral part of soil fertility research.

5.2.2 The Mathematical Equation

While the data in the previous chapter shows that the linear model can fit the data equally well as the curvilinear models, when using annual accumulated yields on the control plots as the pasture yield parameter, the underlying concept of the linear model, is too gross a departure from reality, ie., in reality, both yields and soil supplies of S and P nutrients cannot increase indefinitely as shown by the studies by Brougham (1955). The linear function (Eqn. 4.9) was however presented, to illustrate the reliability of field data to be fitted with several types of mathematical expressions including two curvilinear functions (Eqns. 4.7 and 4.8). Ideally, pasture yield response to increasing soil test values should be curvilinear, rising to a maximum where soil supply for the nutrient in question is no longer the main factor limiting pasture growth. Equations 4.7 or 4.8 both have the right shape and could both provide empirical explanations for the dependency of pasture yields on the supplies of S or P (Tables 4.2, 4.3) However, the form of Equation 4.7 is chosen to explain the dependency of RY to S availability or P availability as this Mitscherlich type model, is considered the simpler of the two. The Equation used is:

$$y = 100(1\text{-}e^{\mathbf{b}x}) \qquad \text{Equation 5.2}$$

where **a** is replaced by 100 as the maximum percentage of yield obtainable, y is RY as the pasture yield parameter instead of actual yield, and **b** remains as the rate constant defining the proportionality of RY to its decrement from the maximum (100%).

When the constant, **a** (Eqn. 4.7), representing maximum actual yield, is replaced by 100%, in calculating RY, the data from different years and different climatic conditions, can then be assembled as the result of a single experiment for a general situation.

5.3 RESULTS FROM THE 1990/1992-BALLANTRAE TRIALS

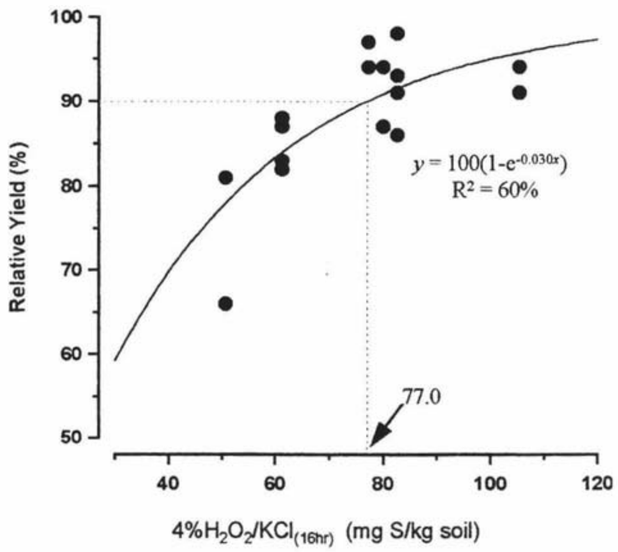
5.3.1 S and P as a Growth Factors

As none of the sites in the 1990/1992-Ballantrae Trials (Table 3.3) were responsive to application of S alone (+S), the resulting RY values calculated as the percentage increase of the mean yield of +S plots above the unfertilised control plots were all above 90%. This relationship was therefore, not worth plotting.

Unfortunately, only two of the eight sites had a +P treatment. Therefore, the effect of S on top of a basal application of P could not be investigated more widely, ie., yield of +SP above +P. This effect of S with basal P was incorporated into another short-term trial series, reported in section 5.4. The effect of P alone, above unfertilised control plots, also could only be investigated at Ballantrae on the LFLF$\underline{M}$ and HFHF$\underline{M}$ sites. In hindsight and if more technical assistance was available, +P fertilised plots should have been included at all sites.

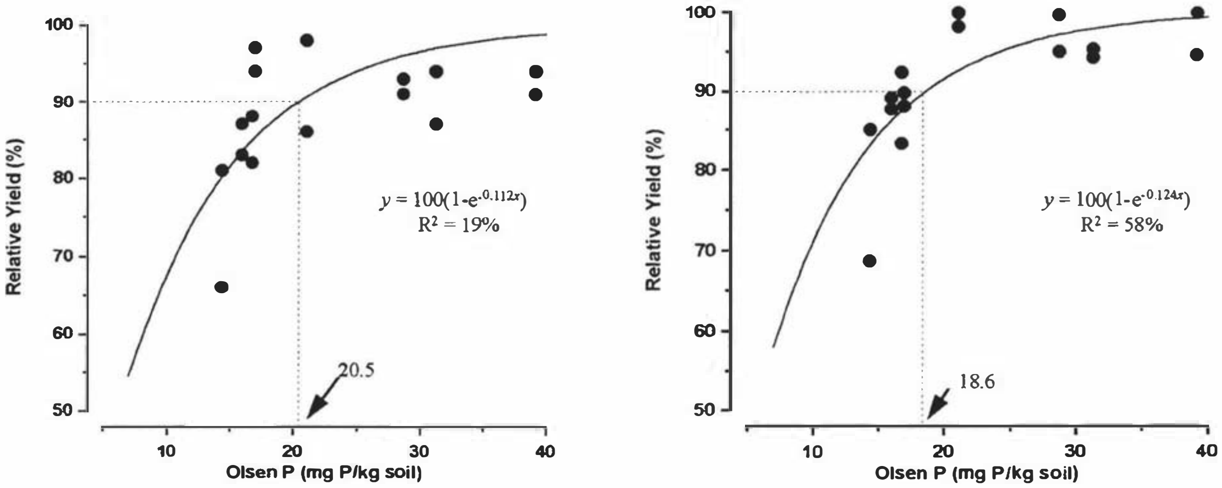
On the other hand, the combined effect of both S and P could be investigated by calculating RY using the mean yields on the +SP fertilised plots and the mean yields on the unfertilised control plots. The effect of P could also be investigated in the presence of basal S, by calculating RY using mean yields on the +SP fertilised plots and the mean yields on the +S fertilised plots.

Figure 5.1 shows the regression between RY, calculated using the mean yields on the +SP fertilised plots and the mean yields on the unfertilised control plots, and the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test. Figure 5.2a shows the regression between the same calculation of RY and Olsen P test. The results show that the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test explained 60% of the variations in RY compared to 19% using Olsen P values.



$$\text{Relative Yield} = \frac{\text{Control}}{\text{+SP Treatment}} \times \frac{100}{1}$$

Figure 5.1 Relationship between RY and $4\%H_2O_2/KCl_{(16hr)}$ extractable S values, where RY was calculated as the percentage increase in yield on the +SP fertilised plots above the yield on the unfertilised control plots.



a) $\text{Relative Yield} = \frac{\text{Control}}{\text{+SP Treatment}} \times \frac{100}{1}$

b) $\text{Relative Yield} = \frac{\text{+S Treatment}}{\text{+SP Treatment}} \times \frac{100}{1}$

Figure 5.2 Relationships between RY and Olsen P test values, where RY was calculated as the percentage increase of yields on the +SP fertilised plots above a) the yields on the unfertilised control plots, and b) the yields on the +S fertilised plots.

The ability of the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test to predict pasture responsiveness to application of S and P together (as in SSP fertiliser application) is evidence that this soil S test can be a reliable index of S availability representing the ability of the soil to supply the effective quantities of S required to utilise both soil and fertiliser P. The results also supports the suggestion from the conceptual model in section 3.4.1 that better predictions of pasture responsiveness to SSP fertiliser would be obtained by assessing the soil if the P applied would induce an S deficiency or not. Further support for this suggestion is obtained when RY is calculated to isolate P as a growth factor using the mean yields on the +S fertilised plots and mean yields on the +SP fertilised plots, ie., with basal S. Figure 5.2b shows that the Olsen P test could now explain 58% of the variations in RY, when the limiting nature of S on the control yield is eliminated.

5.3.2 **Discussion**

In the light of the results from the 1990/1992-Ballantrae Trials, the value of using a soil S test like the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test to diagnose both the current soil fertility level due to historical SSP applications (equivalent to unfertilised control plots) and pasture responsiveness to future SSP application (equivalent to +SP fertilised plots) should be more widely examined. In particular, the relationship between amounts of labile organic S and Olsen P need studying on a wider range of soils. Furthermore, in the context of the conceptual model in section 3.4.1, the good performance of the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test in predicting pasture responsiveness to S plus P application would suggest a good correlation between these soil S values and the amounts of soil available N.

The objectives of the next section is to consider the utility of the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test on a wider range of sites in the Central North Island of New Zealand. It was also an opportunity to investigate further use of the oxidising agent hydrogen peroxide, for its ability to also oxidise mineralisable soil N. This is particularly important for two reasons; i) it has been found that the promotion of legume growth and N inputs by fixation is greatly influenced by the amount of available N (section 3.4.1), and ii) its use as a bi-nutrient soil test may have diagnostic value to assess the effectiveness of strategic N fertiliser use.

5.4 THE MAF TRIALS

In collaboration with Mr R.G. Smith of MAF Technology Central, several trial sites (referred to as MAF trials from here on) were selected to represent a range of soil type with varying fertiliser histories as well as varying climatic conditions (Table 5.1). The trials were conducted over a period of six spring-summer months (October-November, 1990 to March-April, 1991) to ensure sufficient time for legume growth response to applied fertiliser.

5.4.1 **Establishment of Field Trials**

5.4.1.1 ***Methods***

Treatments and Layout

MAF Technology North Central conducted field trials throughout the North Central region to evaluate pasture S responsiveness during 1989-1990. Twelve plots were laid out with six replicates providing two treatments, plus-S and no-S. The research described in this section was a continuation of these trials. During October - November 1990, two additional treatments were added to these trials to include N fertilisation to examine whether responsiveness of pastures to S influenced the effectiveness of strategic fertiliser N use. Strategic N fertiliser use refers to a predicted feed shortage for the grazing animal. In the Central North Island, these deficits of feed demand over growth usually occur in late winter/early spring.

Table 5.1 Some chemical characteristics of the topsoils (0 - 75mm), fertiliser history and some site characteristics of the MAF trials.

Site Number	Location	Soil Group [Soil Type] (NZ classifications)	Average Annual Rainfall (mm)	P retention (%)	pH	Total N (mg/kg)	Total P (mg/kg)	Total S (mg/kg)	Ca-P (mg/kg)	Olsen P (mg/kg)	Fertiliser History
MAF/1	Alfredton	YGE-YBE [Mahoenui]	1215	63	5.67	5567	677	431	10.5	16.2	200kgSSP prior '85, No fertiliser since
MAF/2	Hunterville	YGE-YBE [Taihape]	959	74	5.31	3000	400	192	6.4	13.8	not known
MAF/3	Waituna West	YBE [Kiwitea]	1008	64	5.64	4267	837	537	8.0	15.0	200kgSSP/ha over 20 years
MAF/4	Flock House	YBS [Pukepuke]	880	83	5.54	3033	737	449	4.1	17.4	not known
MAF/5	Kopane	Alluvial [TeArakura]	900	83	5.76	3467	820	532	6.5	22.4	200kgSSP/ha over 25 years
MAF/6	Himatangi	YBS [Pukepuke]	935	87	6.30	3633	730	640	9.1	16.2	200kgSSP/ha over 25 years
MAF/7	Tinui1	YGE-YBE [Whareama]	892	81	5.06	2833	430	383	9.5	18.1	250kgSSP prior '85, Since 100kg DAP Jun,Jul,Aug
MAF/8	Tinui2	YGE-YBE [Whareama]	852	62	5.56	3367	710	437	7.0	20.0	200kgSSP prior' 85, '85-'89: Alternate supreme and 200 kgSSP
MAF/9	Matapiro	YGE [Matapiro]	524	75	5.38	3933	870	571	5.7	16.4	not known

The additional N treatments were obtained by splitting existing plots into halves providing twenty four plots on each site, consisting of four treatments in six replicates (Table 5.2). The plus-S plots were re-topdressed with S as gypsum at 33kg S/ha· To one half, N was added as urea at 25kg N/ha. To one half of the no-S treatment, N was also added as urea at 25kg N/ha. The whole trials were re-topdressed with P at a rate of 40kg P/ha as MCP.

Table 5.2 Summary of treatments and application dates to MAF trials.

Site	+SP		+PN		+SPN	
	33kgS/ha	**17kgS/ha**	**25kgN/ha**	**25kgN/ha**	**33kgS/ha + 25kgN/ha**	**17kgS/ha + 25kgN/ha**
MAF/1	8-Oct		8-Oct		8-Oct	
MAF/2	5-Oct	10-Dec	5-Oct	10-Dec	5-Oct	10-Dec
MAF/3	8-Nov		8-Nov		8-Nov	
MAF/4	19-Oct		19-Oct		19-Oct	
MAF/5	5-Oct	29-Nov	5-Oct	29-Nov	5-Oct	29-Nov
MAF/6	5-Oct	30-Nov	5-Oct	30-Nov	5-Oct	30-Nov
MAF/7	9-Oct		9-Oct		9-Oct	
MAF/8	9-Oct		9-Oct		9-Oct	
MAF/9	12-Oct		12-Oct		12-Oct	

* **Together with the first doses of S and N fertilisers, basal applications of phosphorus (40kgP/ha) and potassium (50kgK/ha) were applied as MCP and KCl respectively. Molybdenum (175gMo/ha) was also sprayed on as a solution of $Na_2MoO_4.5H_2O$.**

Three out of the nine sites (MAF/2, MAF/5, and MAF/6) received second applications of S at the rate of 17kgS/ha and N at the rate of 25kgN/ha after the first harvests giving a total of 50kg/ha of both S and N in these trials. This fertiliser application strategy was employed to maintain the S supply to pasture despite leaching events that may occur. The other trials did not receive much rain during the first period of summer 1990 so that by the time of the first harvest, they were considered too dry and the second applications of S and N were not required (Table 5.2). A basal application of P was also applied to all the plots during each fertiliser application event, from the beginning of the trials in 1989. P is still included in the labels of the treatments, despite it being applied as a basal application, to be consistent with the notations used earlier at Ballantrae.

Pasture Production

Pasture production at each site was assessed by mowing a known area of each plot in the absence of grazing animals, except at Hunterville where pasture production was measured with a capacitance probe. Mowing trials have the advantage of being able to compare a large number of treatments with adequate replication at relatively low cost. The disadvantages include the creation of an artificial pasture sward and the return of nutrients as pasture clippings instead of excreta. Measurement of pasture production using movable exclosure cages in the presence of grazing animals adopted at Ballantrae (Chapter Three), overcomes the disadvantage of mowing without animals but involves a much higher cost and greater variability than mowing techniques for the same number of treatments.

Morton *et al.* (1995) compared the effect of mowing and movable cage techniques on response to P fertiliser throughout New Zealand. They showed that, while absolute yields were under-estimated by 21-37% from mowing compared with cutting movable cages under grazing, the response of pasture production to P fertiliser were similar, using the two techniques. It is assumed in this study that pasture responses, measured by the capacitance probe is also similar to the mowing technique, despite the difference in the absolute yields measured.

After recording the weight of fresh clippings, a sub-sample (200g) was oven dried from which the dry weight/fresh weight ratio was assessed. For assessment of legume production, hand cut samples from each plot were bulked into treatments and mixed thoroughly. These samples were then dissected into grass and legume components.

5.4.1.2 ***Results***

During the spring-summer of 1990/1991, between two and four harvests were taken at intervals of 6-10 weeks depending on the rate of growth which was mainly a function of available soil water. Tables 5.3 and 5.4 shows the accumulated total herbage yields and legume yields during this period respectively. This problem caused by the effect of rainfall (climate) on yield potential is covered in the development of the pasture growth model in Chapters Six and Seven.

Total Herbage Yield

At all sites, the yields obtained on the plots where S and N were applied together (+SPN), were significantly greater from the control (+P) in the presence of a basal application of P, at the 90% level of confidence. Only four of the nine sites showed significant differences in yield on the +SP treatment above the +P. In contrast, seven of the nine trials responded to application of N, ie., yield of +PN treatment above +P. The general responsiveness to N confirms the view discussed by Ball and Field (1985) that the N economy of legume based pastures remain the key limiting factor. As discussed in Chapter Three, application of S and P at the 1990/1992-Ballantrae Trials increased legume yields and is the main route to increasing N supply.

Table 5.3. Accumulated total herbage yield on the MAF trials.

Site	Number of Harvests	Accumulated Total Herbage Yield (kgDM/ha)				$\text{LSD}_{\alpha = 0.1}$
		+P	+SP	+PN	+SPN	
MAF/1	2	1494_c	2040_b	2073_b	2520_a	296
MAF/2*	4	5094_b	5288_b	5496_b	6029_a	439
MAF/3	3	1790_b	1854_b	2054_a	2049_a	157
MAF/4	2	1826_b	2032_{ba}	1766_b	2134_a	275
MAF/5	4	2302_c	2448_b	2562_{ba}	2614_a	138
MAF/6	5	2741_b	2720_b	3278_a	3227_a	291
MAF/7	2	1049_b	1003_b	1269_a	1225_a	133
MAF/8	2	1343_c	1991_b	1915_b	2450_a	187
MAF/9	3	1338_d	2093_b	1535_c	2442_a	106

abcd = T Grouping ($\alpha = 0.1$)

* Capacitance probed

▨ Significantly different (increase) from the control

Legume Yield

The legume yields obtained with application of S together with P (+SP) were significantly higher at most sites than legume yields obtained with application of P only (+P). This again shows the dependency of the utilisation of P for legume growth on available S. In general, application of N fertiliser had detrimental effect on legume growth. When N fertiliser was applied on top of S and P together, ie., +SPN compared with +SP, the detrimental effect of N was observed at six of the nine sites. In contrast, this detrimental effect of N on legume growth was observed on only two of the sites in the absence of S, ie., +PN compared with +P. This provided further evidence of the dependency of P on S. During these spring-summer months, the positive effect of S and P fertilisers, generally outweighed the detrimental effect of N fertiliser on legume growth.

Table 5.4 Accumulated legume yields on the MAF Trials.

Site	Accumulative Legume Dry Matter (kgDM/ha)				LSD$_{\alpha=0.1}$
	+P	+SP	+PN	+SPN	
MAF/1	353_b	646_a	261_b	721_a	102
MAF/2	1428_c	2282_a	1202_c	1717_b	282
MAF/3	834_{ba}	886_a	809_b	732_c	75
MAF/4	374_c	703_a	335_d	653_b	37
MAF/5	1008_b	1176_a	813_c	959_b	64
MAF/6	285_a	205_b	269_a	115_c	26
MAF/7	367_b	483_a	389_b	404_b	48
MAF/8	216_c	417_a	301_b	445_a	33
MAF/9	194_d	1003_a	248_c	891_b	29

abcd = T Grouping ($\alpha = 0.1$)

▨ Significantly different (increase) from the control

▩ Significantly different (decrease) from the control

5.4.2 Soil Testing

5.4.2.1 *Methods*

Seven topsoil (0-75mm) core samples were collected from each plot prior to the fertiliser application during spring 1990. The samples were air dried and grinded to pass through a <2mm sieve. Sub-samples from the previous no-S and plus-S treatments were then bulked, from which chemical analysis were conducted.

Hydrogen Peroxide Extractants

The method for extraction using 4% concentration of hydrogen peroxide was reported in section 4.3.3.4. A weaker concentration of 1% was also investigated given that $KCl_{(16hr)}$ did show some potential as an index of S availability.

As a result of the widespread N response observed in this series of trials, the extractants were also analysed for the amounts of extractable N they contain. It was hoped that the extractable N levels may show some relationship with pasture N responsiveness, allowing the $x\%H_2O_2/KCl_{(16hr)}$ extractants to be used as bi-nutrient soil tests. This was of particular interest because for many plants, the ratio of protein S to protein N is nearly constant under differing conditions of S and N supply (Stewart *et al.*, 1966; Anderson, 1975). The return of S and N to the soil as plant material means that S and N may maintain their stoichiometric relationship in soil organic matter being subject to the same decomposition processes that are simulated here using the hydrogen peroxide oxidising agent.

After filtration (section 4.3.3.4), the extracts were divided and a drop of concentrated sulphuric acid was added to 10mls of extract destined for N analysis. They were then dried in an oven overnight and made up to volume again with deionised water. This step was necessary to eliminate the hydrogen peroxide that would interfere with the analysis for N. Both the NO_3^--N and NH_4^+-N extracted were analysed using a Technicon autoanalyser (Series II) following the method of Kamphake *et al.* (1978). The amounts of extractable S and N are shown in Table 5.5.

5.4.2.2 *Results and Discussion*

The amounts of S and N extracted are shown in Table 5.5. The amounts of S extracted using the 1%H_2O_2/KCl$_{(16hr)}$ test on the previous no-S plots ranged from 59 - 156mg S/kg soil while the plus-S plots ranged from 71 - 178mg S/kg soil. The amounts of N that were simultaneously extracted in this extractant ranged from 119 - 470mg N/kg soil and 141 - 529mg N/kg soil in the previous no-S and plus-S plots respectively. Using the 4%H_2O_2/KCl$_{(16hr)}$ test, the amounts of S extracted on the previous no-S plots ranged from 79 - 255mg S/kg soil while the plus-S plots ranged from 90 - 239mg S/kg soil. The amounts of N that were simultaneously extracted in this extractant ranged from 258 - 1100mg N/kg soil and 291 - 1035mg N/kg soil in the previous no-S and plus-S plots respectively.

Table 5.5 Amounts of S and N extracted, using 1%H_2O_2/KCl$_{(16hr)}$ and 4%H_2O_2/KCl$_{(16hr)}$ extractants of soils from the MAF trials.

Site	Previous S Treatment	1%H_2O_2/KCl$_{(16hr)}$			4%H_2O_2/KCl$_{(16hr)}$		
		S (mg/kg)	NH_4-N (mg/kg)	NO_3-N (mg/kg)	S (mg/kg)	NH_4-N (mg/kg)	NO_3-N (mg/kg)
MAF/1	- S	74	295	4	120	553	1
“	+ S	103	280	3	154	580	1
MAF/2	- S	59	179	1	79	257	1
“	+ S	72	252	1	90	290	1
MAF/3	- S	69	202	5	124	460	2
“	+ S	71	200	5	130	553	2
MAF/4	- S	156	462	8	135	787	5
“	+ S	178	520	9	149	783	6
MAF/5	- S	122	360	2	126	567	3
“	+ S	126	357	3	139	653	2
MAF/6	- S	131	327	4	255	1097	3
“	+ S	157	375	4	239	1033	2
MAF/7	- S	92	237	5	101	643	6
“	+ S	114	248	9	121	820	8
MAF/8	- S	69	113	6	94	643	4
“	+ S	82	133	8	116	660	6
MAF/9	- S	77	173	8	143	987	9
“	+ S	98	177	9	158	980	10

Both the amounts of S and N extracted from the previous plus-S soils were higher than the no-S soils. This indicates that amounts of S and N extracted were derived from S and N recently incorporated into organic matter via assimilation as protein in plant material or via microbial material and their subsequent decomposition. This is supported by the strong correlation between the amounts of S and N extracted with both the 1%H_2O_2/KCl$_{(16hr)}$ and 4%H_2O_2/KCl$_{(16hr)}$ extractants (Fig. 5.5). Therefore, analysing for both S and N in the x%H_2O_2/KCl$_{(16hr)}$ extractants, appear to have the potential to used as bi-nutrient soil tests.

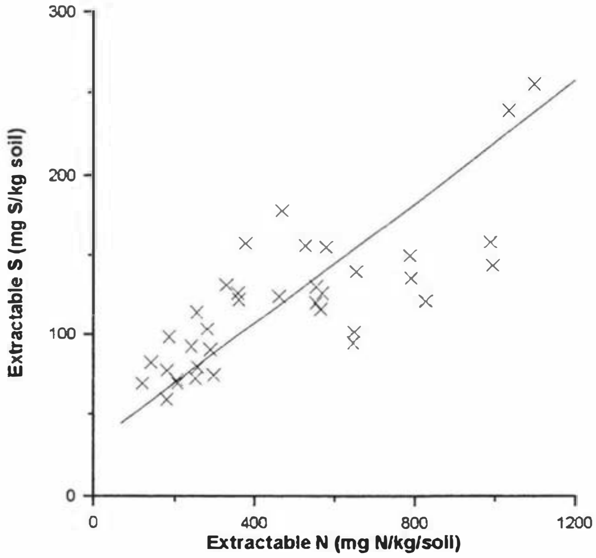


Figure 5.3 Relationship between the amounts of S and N extracted using 1%H_2O_2/KCl$_{(16hr)}$ and 4% H_2O_2/KCl$_{(16hr)}$ extractants.

The amounts of S extracted in this series of trials were generally higher than the amounts extracted at Ballantrae where 4% H_2O_2/KCl$_{(16hr)}$ extractable S ranged from 50.7mg S/kg soil at the LFNFL site to 105.3mg S/kg soil at the HFHFL site (Table 4.1). An unforseen effect that was not considered in the design of the MAF Trials is that, application of P fertiliser does have a marked effect on the build up of labile soil organic S as indicated by the study of Nguyen and Goh (1990) and noted in the Ballantrae farmlets by Sakadevan *et al.* (1993). The higher levels of extractable S on these sites are probably due to application of P in the previous two years

5.4.3 Pasture responses to S and N

The fertiliser regime used, was designed so that the RY device can be used to isolate S as a growth factor. This was achieved by calculating RY, using the mean yield on +SP fertilised plots, above the mean yield of the +P fertilised plots, ie., with basal P. Alternatively, RY can be assessed using the mean yield on the +SPN fertilised plots above the +PN fertilised plots, ie., with basal P and N.

The fertiliser regime adopted, was also designed to isolate the effect of strategic fertiliser N as a growth factor. This was achieved by calculating RY, using the mean yields on the +PN fertilised plots above the mean yields of the +P fertilised plots, ie., with basal P. Alternatively, the mean yields of the +SPN fertilised plots above the mean yield on the +SP plots can be used, ie., with basal S and P.

Figures 5.4a,b and 5.5a,b shows the relationship between these calculations of RY and extractable S and extractable N respectively. These figures shows that neither of the extractable S, nor extractable N in both the 1%$H_2O_2/KCl_{(16hr)}$ and 4% $H_2O_2/KCl_{(16hr)}$ extractants, could explain the variations in RY. The use of the traditional calcium phosphate extractable S test (Ca-P) (Table 5.1) also could not explain the variations in RY due to applied S (lack of relationship not shown).

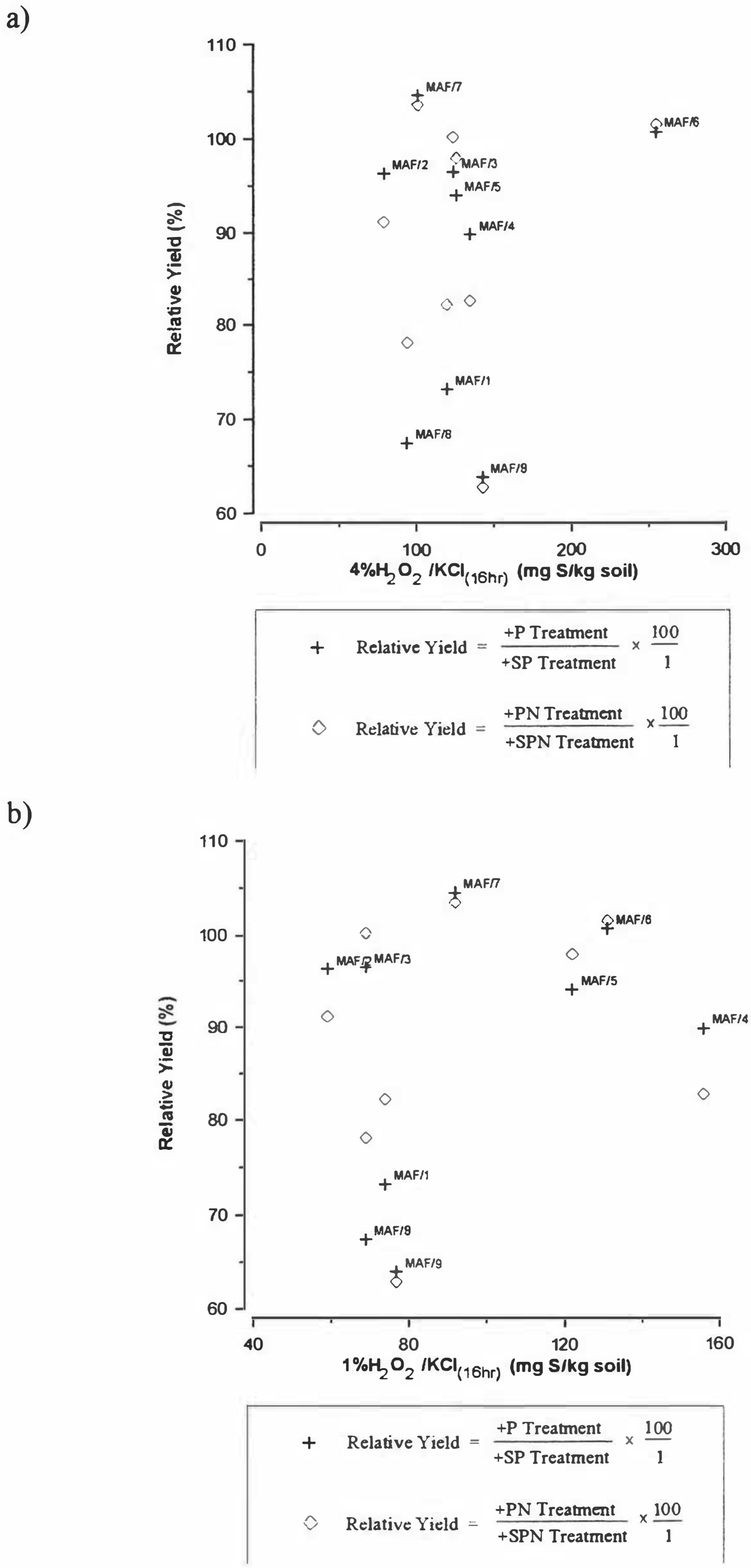


Figure 5.4 Relationships between RY and a) $4\%H_2O_2/KCl_{(16hr)}$ extractable S, and b) $1\%H_2O_2/KCl_{(16hr)}$ extractable S.

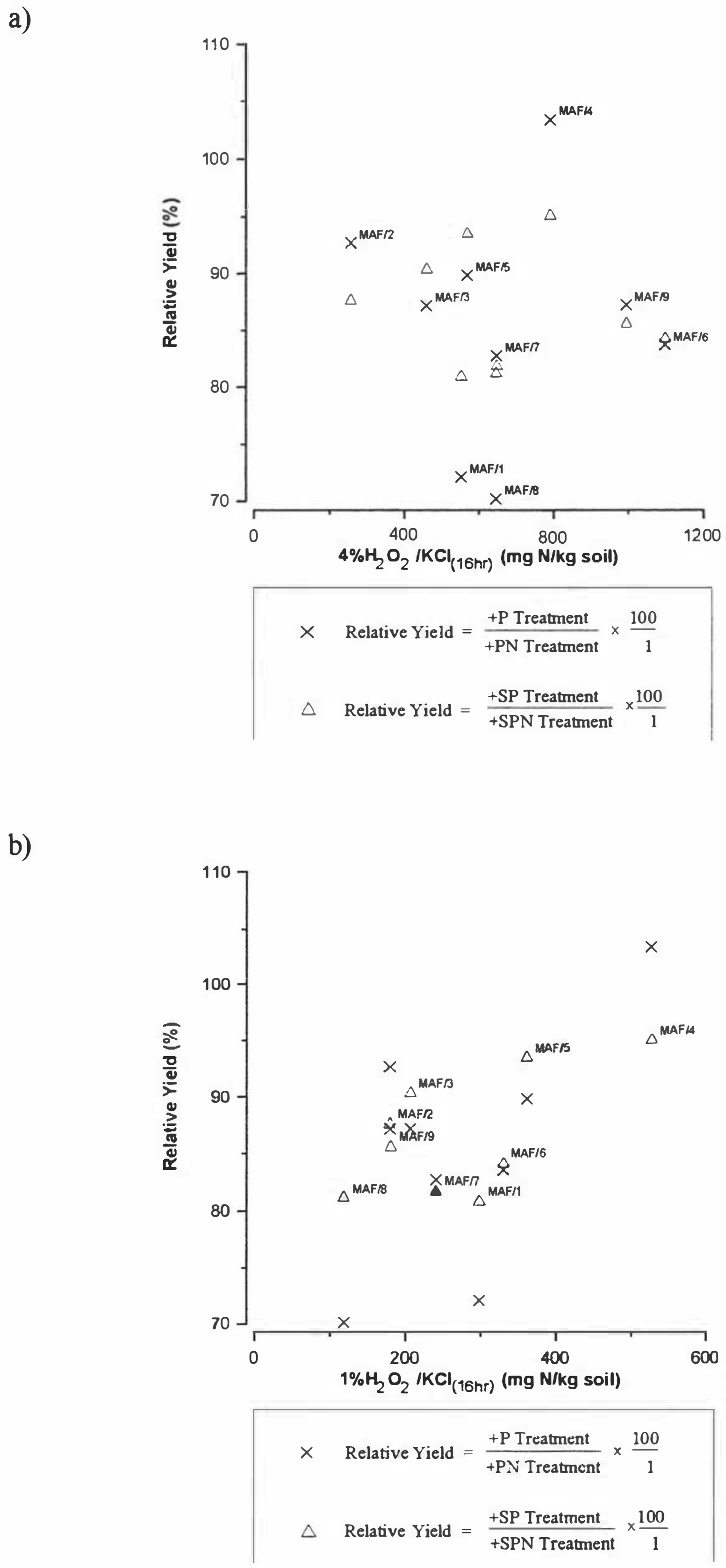


Figure 5.5 Relationships between RY and a) 4%H_2O_2/$KCl_{(16hr)}$ extractable N, and b) 1%H_2O_2/$KCl_{(16hr)}$ extractable N

There are a number of possible reasons why these soil tests could not explain the variations in RY. Firstly, the high range of $4\%H_2O_2/KCl_{(16hr)}$ extractable S (ranged from 79 - 255 mg S/kg soil on the previously no-S plots, Table 5.5) compared to the 1990/1992-Ballantrae Trials (ranged from 51 - 105 mg S /kg soil, Table 4.1) in which pasture growth was not responsive to the +S treatment suggests that on these soils, pasture growth should be non-responsive to additional S. Yield data in Table 5.3 shows that this was not the case. It may be argued that the $4\%H_2O_2/KCl_{(16hr)}$ test extracts such a large component of the organic S fraction in the MAF Trials (22 - 41% of total S) that it is no longer a sensitive index of a smaller labile fraction that is involved in influencing short-term pasture growth. However, this is unlikely because the weaker $1\%H_2O_2/KCl_{(16hr)}$ extractable S and Ca-P extractable S removed lower amounts of S (13-34% and 1-3% of total S respectively), but were also not correlated with RY calculated from pasture growth response to applied S with basal P.

Secondly, the validity of using the RY device with basal P to isolate S and N as growth factors has to be questionable because calculating RY from yield data with basal P, does not take into account that P has more influence on legume growth than S. As improving soil P status with applied fertiliser has a marked impact on the build up of labile organic S, it is likely that application of P to the control plots may have induced S deficiency in the control plots. At the 1990/1992-Ballantrae Trials, it was suggested that induced S deficiencies by applied P was the main reason for the better performance of the $4\%H_2O_2/KCl_{(16hr)}$ test at predicting responses to application of S plus P compared to the Olsen P test (Figs. 5.1, 5.2a). If applied P do induced some S deficiencies, then basal P would have produced inflated RY values for pasture response to S using yields on the +SP treatment above the +P as the control, which may explain the lack of a relationship between RY and the $4\%H_2O_2/KCl_{(16hr)}$ test in these MAF Trials. They may also explain why the sites in the MAF Trials generally had lower RY values (calculated from yields of the +SP and +P treatments) associated with higher

$4\%H_2O_2/KCl_{(16hr)}$ test values compared to the RY values (calculated from yields on the +SP and unfertilised control plots) at the 1990/1992-Ballantrae Trials.

Thirdly, the differences in P retention values of the different soil types (Table 5.1), means that each level of soil S supply (measured by the $x\%H_2O_2/KCl_{(16hr)}$ extractants), is interacting with different amounts of available P, despite the basal application of P.

When the $x\%H_2O_2/KCl_{(16hr)}$ extractable N were used for the regressions against RY to isolate the influence of strategic applications of N on pasture growth (Figs. 5.7a,b), the $1\%H_2O_2/KCl_{(16hr)}$ extractant showed that it has potential to predict pasture responsiveness. Together with the strong correlation with extractable S (Fig. 5.5), the potential of the hydrogen peroxide extractants as bi-nutrients is worth investigating for future research.

Although it is common practice to apply basal P in order to isolate S as a single growth factor, interactions between S and P availability remains and confound the value of RY which purports to represent the single S fertility factor. In conclusion, application of basal P in a field trial design cannot be used to normalise the effects of S and climate on pasture growth because more favourable climate conditions for growth may induce unknown levels of S deficiencies. The effect of climate therefore, still remains the main factor creating different levels of pasture responses to similar levels of soil fertility (eg., Hedley *et al.*, 1995).

5.5 GENERAL DISCUSSION AND CONCLUSIONS

At Ballantrae the 4%H_2O_2/KCl$_{(16hr)}$ extractable S test was shown to have potential as an indicator of general soil fertility as indicated by its ability to predict not only the yields as affected by historic SSP fertiliser application, but also yield responses to further application of S plus P fertilisers (+SP, equivalent to SSP application).

Perrott and Sarathchandra (1987) have shown that most of the residual P from recent SSP applications in some New Zealand soils are present as inorganic P, which is reflected in increases in Olsen P test. Similar increases in Olsen P were reported by Roberts *et al.* (1995). The strong correlation between the 4%H_2O_2/KCl$_{(16hr)}$ extractable S test with the Olsen P test is therefore, further evidence that the 4%H_2O_2/KCl$_{(16hr)}$ extractable S test could be used more widely as an indicator of general soil fertility status as affected by SSP fertiliser application. It was therefore important to investigate the use of the 4%H_2O_2/KCl$_{(16hr)}$ extractable S test on a wider range of soil types and climatic conditions.

The MAF Trials were established in the hope that S and N could be isolated as growth factors using the RY device by adopting a basal P application in the design of the field trials. These trials were a continuation from a series of trials that were established two years earlier by Central MAF Technology. Unforseen at the time was that the +S alone treatments at the 1990/1992-Ballantrae Trials (which were conducted concurrently) were continuing not to stimulate pasture growth even at the LFNF sites. The non-responsiveness of the 1990/1992-Ballantrae Trials to the S alone treatment (+S) meant that all the sites chosen were not deficient in S and the 4%H_2O_2/KCl$_{(16hr)}$ extractable S test could not be used to explain the dependency of pasture growth on S as a growth factor. As the 1990/1992-Ballantrae Trials were continuing, it was becoming apparent that S deficiencies occurred only after being induced by applied P. This probably contributed to the better ability of the 4%H_2O_2/KCl$_{(16hr)}$ extractable S test than the

Olsen P to predict pasture responses to +SP the treatment. The use of $4\%H_2O_2/KCl_{(16hr)}$ extractable S as an alternative to Olsen P need to be examined further, despite the poor predictions of RY response to S in the MAF Trial series. It is suggested that as S and P interaction confounded the use of RY to isolate S as a growth factor. On hindsight, additional pasture yield data from unfertilised control plots at the MAF Trials plots would have added value to the rest of the data so that the effect of the S and P interaction could have been isolated.

In conclusion, the S and P interaction is an integral part of legume based pastures that should be incorporated into the design of field experiments, rather than designing the field experiments to isolate the effect of each nutrient. Given the potential of the $x\%H_2O_2/KCl_{(16hr)}$ extractants to be used as a bi-nutrient soil tests, further examinations of their uses should be supported by better field data.

While the RY device may be used to improve understanding of S and P interactions in SSP fertilised pastures it has limited practical application to fertiliser management because of the difficulty and errors associated with converting RY into actual yield at each new site.

At this point, it was considered that research efforts were better directed towards developing a framework to describe pasture growth in terms of actual yields, as affected by both the fertility of the soil and climate.

CHAPTER SIX

PASTURE GROWTH AS AFFECTED BY CLIMATE AND SOIL FERTILITY

6.1 INTRODUCTION

Soil test models have shown that Mitcsherlich type functions have offered good empirical approximations of the dependency of pasture growth on the supply of nutrients (Black, 1992; Colwell, 1994). However, the use of RY (relative yield, Chapter 5) as the pasture yield parameter, means that actual yields associated with each level of soil nutrient supply, estimated with chemical extractants, are not simply proportional to a single corresponding maximum yield. Maximum yields may vary as much as 5 fold from site to site as a function of climate. Use of RY, with such large variation in actual yield, may not reduce variation in the yield parameter and may fail to improve the explanation of yield by a model using soil test data (Saunders *et al.*, 1987; Saunders *et al.*, 1988).

A large part of the dependency of pasture growth on the soil supply of nutrients is also due to the amount of water available for growth (Power 1983, Hedley *et al.*, 1995). Water is the transport media for the passage of nutrients from soil to plant, however, approximately 95% of the water used by plants is lost through evaporation from the leaf. The amount of water used by plants reflects the impact of available water, temperature and solar radiation on plant growth (Wild, 1990). Power (1983) noted a strong interaction between the availability of water and plant nutrition, and that changing one of these factors can greatly affect responses to the other. Hedley *et al.* (1995) also noted variations from one year to another in the relationships between plant P uptake and Olsen P values, due to differences in the amount of water available.

Thus, rather than calculating RY to normalise the yield parameter between sites of varying maximum yield, it would seem more appropriate to normalise yield with the amount of water that was used for growth, ie., to define growth rates as a function of plant water use. Such a mechanistic model is developed and discussed in this chapter.

6.1.1 Water-Use Efficiency and Soil Fertility

Power (1983) defined water-use efficiency (*WUE)* as the yield of plant product produced per unit of water used. Mathematically, it is expressed as:

$$WUE = \frac{Y}{ET}$$

Equation 6.1

where Y is the quantity of plant product (harvestable yield) produced on a given surface area in a given time period, and ET is evapotranspiration from the same surface area during the same time interval. Ideally, the amount of water use should be estimated from transpiration (T) rates. However, in the field, the only data that is normally available is evaporation (E) records. For pasture at full cover, it can be assumed that all of the water evaporated leaves the canopy as evapotranspiration (Coulter 1973; McNaughton *et. al.* 1979). Evapotranspiration has all the criteria of being a good plant growth driver. It is driven by measured solar radiation which drives photosynthesis and passively results from stomatal opening, i.e., allows the gaseous exchange of reactants and products of photosynthesis (CO_2 and O_2) to the atmosphere.

Of critical importance to farm management is the relationship between *WUE* and the fertility of the soil. The data of Smika *et al.* (1965) showed that the rate of N fertilisation had little effect on grass production when water supply by irrigation was limited to less than 250mm, compared to responses of several thousand kg DM/ha when water supply by irrigation was above 400mm. Likewise, responses to increased water were very modest with no fertiliser N, but increased greatly as the rate of N fertilisation increased. These results indicate that grass response to water availability is dependent on the amount of nutrients contained in the water that passes through the plants during transpiration.

From a modelling point of view, the nutrient concentration of the soil solution in the root zone is central to understanding the relationship between *WUE* and the fertility of the soil. Figure 6.1 shows the interacting components in a grazed pasture system. The evaporative demand or potential evapotranspiration (ET_p) represents the climatic aspect of the system.

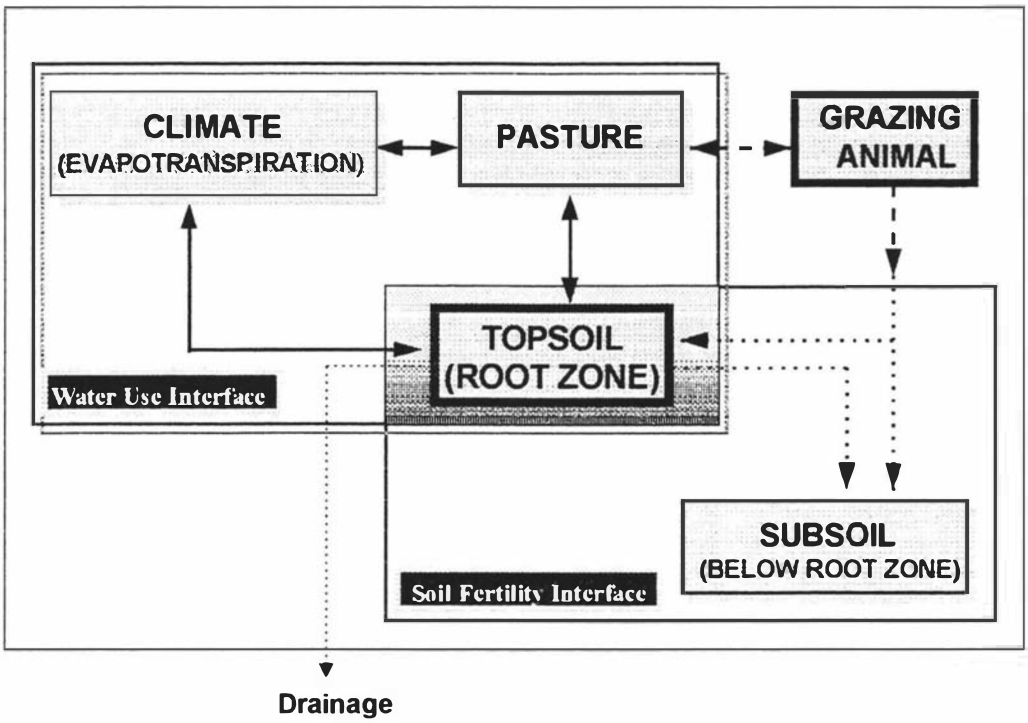


Figure 6.1 The interacting components of a grazed pasture system.

The first step in modelling a grazed pasture system is to compute a soil water budget for the root zone to estimate soil water availability, and the quantity of water that presumably passes through the plant from the roots to the atmosphere during transpiration. Mass balance calculations of the amounts of solutes in the root zone can then be made easier, knowing the inputs and removal of nutrients into and out of the root zone, potentially carried by the water (e.g., Heng, 1991; Sakadevan, 1991).

The objectives of this chapter are: i) to develop a soil water balance model for the Ballantrae farmlets using climatological data to estimate actual evapotranspiration (Et_a), ii) to model pasture yields as a function of Et_a, the quantitative estimate of climate, ie., *WUE,* and iii) to model the dependency of *WUE* on soil fertility.

Such models should make it possible to simulate pasture growth on a daily basis, from a given set of climatological data. The model therefore assumes, that the effects of climate on pasture growth may be adequately represented through average light, temperature and rainfall data.

To evaluate the soil water balance model the predicted soil water contents of the topsoil (0 - 75mm) are compared (Section 6.2.2) with soil water contents that were measured every two weeks, over a twelve month period from Januray 1993 to January 1994. These measured soil water contents were reported in a Masters thesis by del Pino Machado (1994) (1993-Ballantrae Trials). The del Pino Machado study also measured pasture yields from two harvesting regimes of 2 weekly and 4 weekly harvests over the same period. The *WUE* (Equation 6.1) estimated from this set of data will be used in modelling the dependency of *WUE* on the fertility of the soils. The predicted *WUE* values, using soil test results as estimates of soil fertility, are then used in the next chapter (Chapter Seven) for the simulation of pasture growth over the two year period from April 1990 to June 1992, which are compared to the measured values reported in Chapter Three (1990/1992-Ballantrae Trials).

6.2 A SOIL WATER BALANCE FOR BALLANTRAE FARMLETS

All nutrient cycling processes are highly dependent on water and without effective water balance models, the models of pasture growth dependency on water availability and soil supply of nutrients would be of limited value.

6.2.1 **Model Description**

A simple, soil-water balance model of a four-layered, one dimensional soil column system is used to compute daily changes in the soil profile moisture content. Each soil layer is 75mm in depth so that the whole profile is 300mm, assuming that the amount of pasture roots below 300mm is negligible (Barker *et al.*, 1988). A soil column with a surface area of 1 hectare and to a depth of 300mm, is considered an adequate dimension for the accurate modelling of water movements through the topsoil and the root zone (Fig. 6.1).

For any given day ($\Delta t = 1$ day);

$$\Delta SW_{(i)} = R_{(i)} - Drn_{(i)} - ET_{a(i)}.$$

Equation 6.2

For each layer i, $SW_{(i)}$ is soil water content; $R_{(i)}$ is rainfall; $ET_{a(i)}$ is actual evapotranspiration; and $Drn_{(i)}$ is drainage. Each term has the units of mm day^{-1}.

To compute daily $SW_{(i)}$ for each day, rainfall was measured and added to the top layer, assuming that surface runoff is negligible. If $SW_{(1)}$ is greater than the soil water content at "field capacity" ($FC_{(1)}$), then the difference is overflowed as drainage ($Drn_{(1)}$), and becomes rain for the next layer down ($R_{(2)}$), while the value of $SW_{(1)}$ equals $FC_{(1)}$. This "tipping-bucket" process is continued until, $Drn_{(4)}$ becomes the daily drainage (below

300mm) from the whole column representing the root zone, from which leaching losses can be calculated. After the sharing of rainfall between the four layers, $ET_{a(i)}$ is calculated, as described below, and subtracted from $SW_{(i)}$.

Potential evaporation from the surface (ET_p) during each day is estimated from a Priestly and Taylor (1972) calculation, using meteorological data collected at Ballantrae. The climatological data required to calculate daily ET_p are: sunshine hours; maximum and minimum temperatures. The location of the sites, in latitude (for Ballantrae = - 40.38^0 S) is also needed, if incoming solar radiation is not measured. The complex computations and extra data necessary for the use of a Penman equation, like the form given by Coulter (1973), was proven unjustified by Scotter et. al. (1979), with data from grazed pasture on a Fragiagualf soil, 13km from these sites location.

To calculate $ET_{a(i)}$, the ET_p from a surface area (normally in hectares) is firstly shared among the four layers, depending on the fraction of total root mass ($r_{i,}$) contained in each layer.

$$ET_{p(i)} = ET_p \frac{r_i}{\sum_{i=4}^{i=1} r_i}$$

Equation 6.3

In wet soil situations, it is genarally assumed that ET_a will be equal to ET_p. However, under drier conditions, ET_a may be less than ET_p owing to restricted soil water availability. Johns and Smith (1975) compared several approaches for modelling this relationship and found that there is little to be gained by using more complex models (eg., Linacre, 1963; Shaw, 1964; Eagleman, 1971; Linacre, 1973; Johns, 1974), compared to a simple ratio function, which is the approach taken here.

The simple ratio function is based on the assumption that the ratio of ET_a/ET_p for any day can be predicted from the soil water content alone. It is assumed that a certain fraction (F) of the soil water content at "field capacity" (FC) is freely available. For simplicity, it is assumed that F remains constant over the 0-300mm soil depth. After this fraction is exhausted, the ratio of ET_a/ET_p is then assumed to decrease from unity to zero in a linear manner. In these calculations, the soil was allowed to reach zero dryness without setting a lower limit on dryness, ie., no "permanent wilting point". Adding a permanent wilting point did not improve the predictions of soil water content previously (e.g.; Heng, 1991; Sakadevan, 1991), hence, for the purpose of simplicity it was omitted from the present model. $ET_{a(i)}$ were computed on a daily basis as follows:

If $SW_{(i)}/FC_{(i)} > F$, then

$$ET_{a(i)} = ET_p \frac{r_i}{\sum_{i=4}^{i=1} r_i}$$

Equation 6.4

If $SW_{(i)}/FC_{(i)} < F$, then

$$ET_{a(i)} = ET_p \frac{r_i}{\sum_{i=4}^{i=1} r_i} \left\{ \frac{SW_{(i)}}{FC_{(i)}\,(1 - F)} \right\}$$

Equation 6.5

The amount of water that passes through the plants in a given day, is then equal to the sum of $ET_{a(i)}$ from all four layers:

$$ET_a = \sum_{i=4}^{i=1} ET_{a(i)}$$

Equation 6.6

6.2.1.1 *Initial Values*

During sensitivity testing of the model (section 6.2.2.1), the least variability (shown by standard deviation) of the computed water deficits from the observed daily soil water deficits of the topsoils (0-75mm) during 1993, was obtained when F was set at 0.5 (Fig. 6.3b). This value of F was therefore, used in the simple ratio function (Eqn. 6.5) for estimating ET_a.

Soil volumetric water contents measured on the 9 July 1993, when a total of 44mm of rain fell within 5 days before this sampling date, were used as FC. These values were 42mm for topsoil and 156mm for the whole root zone at the HF farmlets, and 35mm for topsoil and 142mm for the whole root zone at the LF farmlets. The lower values observed at the LF farmlets are presumably due to the lower organic matter contents at these sites. The values for the bottom layers (i = 2,3,4) were estimated using the data of Sakadevan (1991) measured on the 5 July, 1989. It is assumed that the hydraulic properties of the soils did not change significantly over time. Any errors caused by this assumption were considered negligible because about 70% of the roots were in the topsoil (Barker *et al.*, 1988), so that the model was not very sensitive to the FC values of the bottom layers. When FC values for layers 2,3 and 4 were altered by +/- 10mm each layer at a time, the total drainage for the whole twelve months varied by only about 5mm, and total ET_a by about 10mm.

6.2.2 **Results**

The twelve month period from January 1993 to Februray 1994 included several alternating wet and dry periods. Consequently, a wide range of soil water contents were observed (Fig. 6.2a). The fluctuations in the computed values are consistent with patterns expected of the top 0-75mm layer.

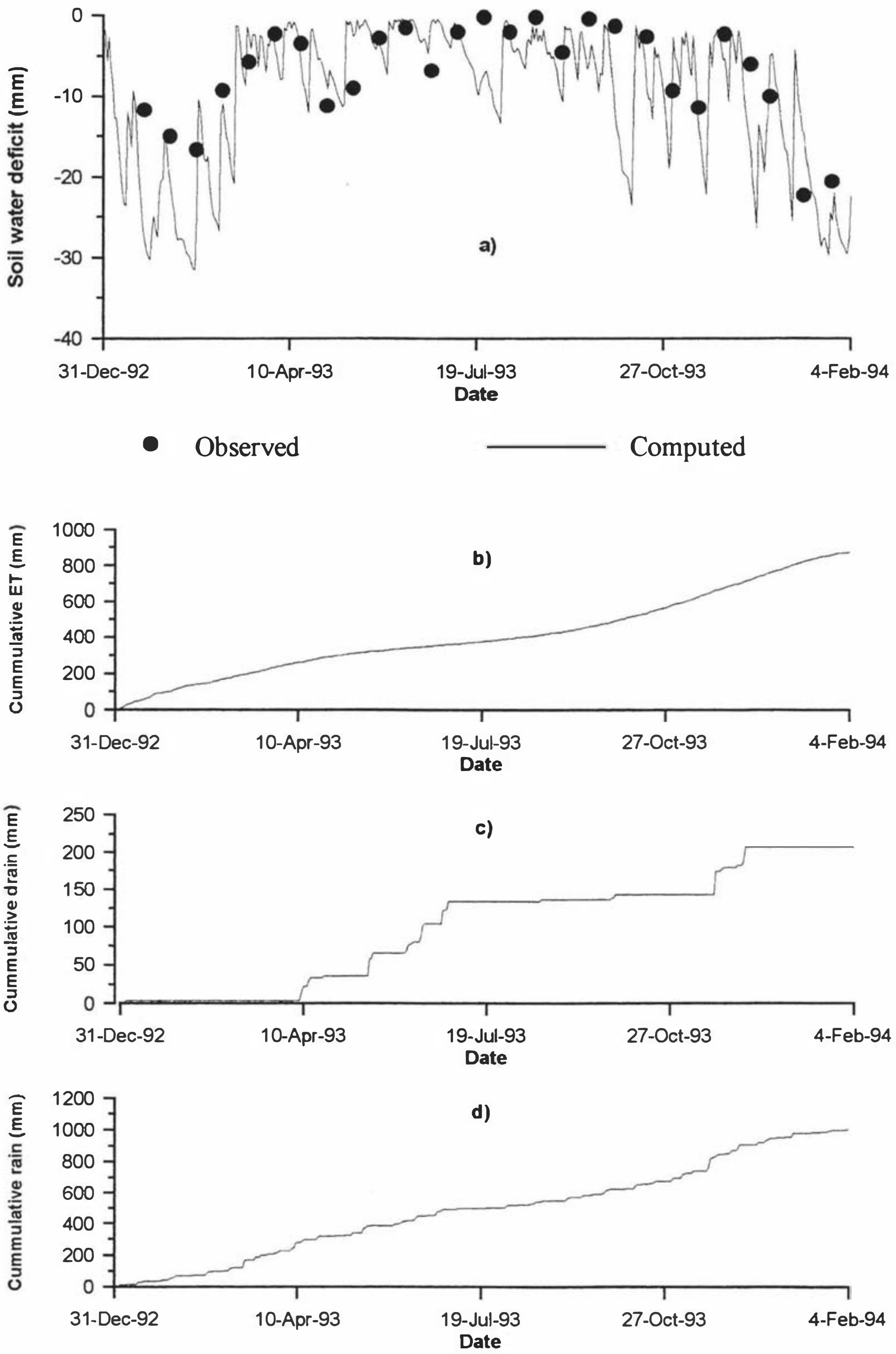


Figure 6.2 a) Computed and measured soil water deficits in the topsoil (0-75mm) from the LFLF farmlet, b) computed cummulative ET_a c) computed cumulative drainage, d) measured cummulative rain, January 1993 to Feburary 1994.

From January 1993 to January 1994, 952mm of rainfall was measured which was slightly below the long term average of 1000-1400mm per annum. Most of the computed drainage occured during early winter, when about 130mm of water drained, and in spring after 80mm of rain fell within two days (20 and 21 November). The total drainage over spring and summer was 73mm. Sakadevan (1991) measured total drainage of 118mm over winter and 103mm over spring, in 1989. While no drainage measurements were taken during 1993 to 1994, the computed values appear to be reasonable estimates of actual drainage at Ballantrae.

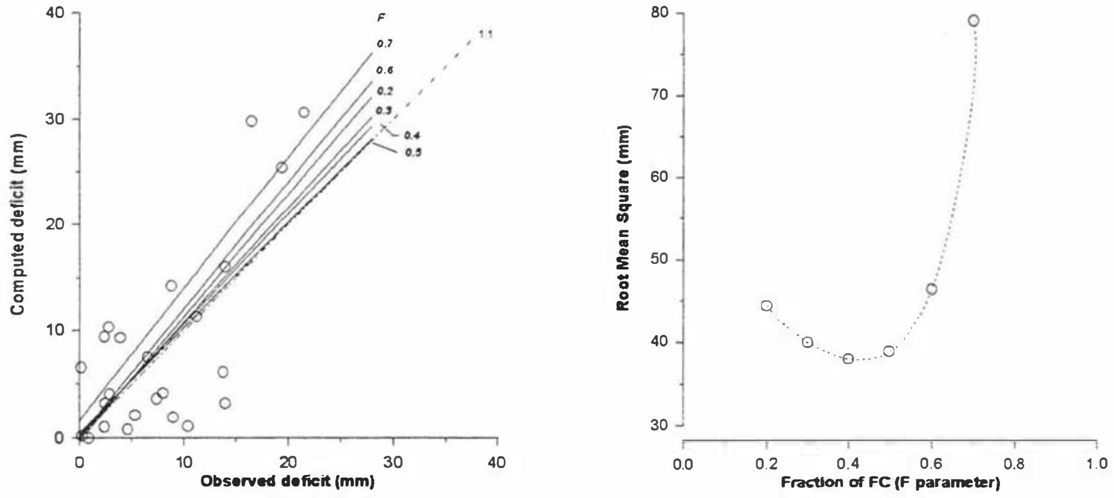
6.2.2.1 *Sensitivity Tests*

In assessing the effect of each *F* value (Eqn. 6.5), investigated as the fraction of FC after which soil water content limits ET_a, the root mean square (RMS) of the magnitude of the differences between observed and computed soil water deficits was used as the criterion for the performance of each value, ie.:

$$\mathrm{RMS} = \left\{ \sum_{n=1}^{n=27} \frac{(SWD_{comp} - SWD_{obs})^2}{26} \right\}^{0.5}$$

Equation 6.7.

The RMS value represents the standard deviation of the computed deficits (SWD_{comp}) from the observed deficits (SWD_{obs}). n is the number of measurements. Twenty seven 2 weekly measurements were made between January 1993 and February 1994 (n= 27). *F* values of 0.2 to 0.7 were tested, using data from the LF farmlets. The results showed that the RMS value was minimum when *F* was set at 0.5 (38.8mm) (Fig. 6.3b). This became the value used for computations.



a)

b)

Figure 6.3 a) Best linear fits to the relationships between observed and computed deficits based on the simple ratio function with varying values of *F* parameter. Plotted points are for *F* = 0.5. b) Effects on root mean square by varying the *F* value.

6.2.3 Discussion

The results from this model show close agreement between computed and observed soil water contents of the top 0-75mm layer. The ET_a output values from this model can therefore, be used with confidence, as estimates of the amount of water that passes through the plants each day.

6.3 MODELLING THE DEPENDENCY OF PASTURE GROWTH ON ACTUAL EVAPOTRANSPIRATION (ET_a) AND PASTURE MASS, STANDING AS COVER: WATER-USE MODEL

Complications arise when calculating *WUE* (Equation 6.1) because pasture growth with time is not linear. Brougham (1955) has shown that pasture growth follows sigmoid patterns with time. His data showed that daily increments of growth during the first 3-4 weeks were increasing as ground cover by leaves increased, until maximum absorption of light energy was obtained. For the next 4-5 weeks, growth rates were approximately constant and at a maximum level, presumably as absorption of incident light had reached a maximum value. During the last phase, the rate of increase of yield declined, probably due to the transition from vegetative to reproductive growth. Brougham (1959) found that yield ceilings, and the time intervals required to reach them, also showed marked seasonal trends with the lowest ceilings recorded in the winter and the highest in the spring.

For modelling of these pasture growth patterns, Brougham (1956) showed that the logistic function offers a reasonable empirical approximation to the dependency of pasture growth on an index of leaf area. Logistic functions have been used in many modelling studies since, e.g. Morley (1968), Thornley (1990), Woodward (1995). In these cited models, pasture growth rates are generally estimated as the amount of harvestable dry matter produced per day, assuming different coefficients for each season.

6.3.1 Logistic Model Description

In this study, a mathematical model is developed based on the logistic growth curve, but the growth rates are estimated using ET_a instead of time (Fig 6.5a), i.e., the growth rates units are 'kg/ha/mm' instead of 'kg/ha/day'. At a site of defined soil fertility, *WUE*, the average amount of pasture yield per unit of ET_a, integrates the effects of temperature, soil moisture and solar radiation on plant growth one 2 week harvest period (section 6.3.2). As daily ET_a already varies from one season to another (Fig 6.2), the use of 'climatic' growth rates means that separate growth curves for each season are not required. i.e., pasture growth can be represented by a single *WUE* function throughout the year.

Pasture growth is modelled as:

$$\frac{dY}{dET_a} = \mathbf{a(ET_a)}Y - \mathbf{b}Y^2 \qquad \text{Equation 6.8}$$

This form of the pasture growth curve was adapted from the model of Woodward (1995), which defined the growth rates as a function of time instead of ET_a. The present model implies that pasture growth rates are simply a function of the physiological factors affecting the sward, as climatic factors are already incorporated. This model was chosen because i) physiological meaning can be attached to the two terms explaining the variations in yield with ET_a., and ii) its shape complies with logistic growth pattern measured by Brougham (1955).

The first term on the right $\{\mathbf{a(ET_a)}Y\}$ represents the net balance between the rate of new growth and the rate of senescence. This term is linearly related to pasture mass and is dependent on accumulated ET_a according to the climatic parameter $\mathbf{a(ET_a)}$. The compound representation of this parameter is to emphasise that the units are kg/kg/mm. The second term $\{\mathbf{b}Y^2\}$ represents a damping of growth due to self shading within a sward canopy. It is not linear and does not depend on the accumulated amount of ET_a. **b** has the units of ha/kg/mm.

The first and second terms taken together comprise a logistic growth curve with ceiling yield:

$$Y_{ceiling} = \frac{a(ET_a)}{b} \qquad \text{Equation 6.9}$$

and maximum growth rate:

$$g_{ceiling} = \frac{a(ET_a)^2}{4b} \qquad \text{Equation 6.10}$$

6.3.2 Yield Measurements

The data for estimating the growth rates as affected by pasture mass, or the amount of harvestable yield already existing as cover, were reported in the Masters Thesis by del Pino Machado (1994). Seven sites also located at Ballantrae, were selected for del Pino Machado's study (1993-Ballantrae Trials). The Olsen P values for these sites ranged from 9.0 to 59.3mg P/kg soil (Table 6.1), on a LFNF farmlet and the HFHF farmlet respectively. These values, when compared to the values of 14.4 to 39.2mg P/kg soil, obtained on the sites from the same farmlets, reported in Chapter Three reflect the specific fertility level of each trial site caused by variations in SSP fertiliser input and the non-uniform return of nutrients in urine and dung. The data set included pasture yields from two harvesting regimes with either 2 weekly or 4 weekly intervals between cuts.

Pasture mass was measured as harvestable yields, using the enclosed cage technique described in Chapter Three. The total amounts of ET_a accumulated in each 2 week harvest period, were calculated using the model described in section 6.2. These values ranged from 10.9 mm in winter to 58.7 mm in summer, corresponding to average daily ET_a values over a two week period of about 0.7 mm in winter to about 4.2 mm in summer (actual range was 0.5 to 5.8 mm). Table 6.1. shows the range of harvestable yields that were obtained using the two harvesting regimes.

Table 6.1 Ranges of yields from the 2 weekly and 4 weekly harvesting regimes showing a minimum measured in winter and a maximum measured in summer in the 1993 Ballantrae trials, and Olsen P values.

Site Number (Location)	**Olsen P (mg P/kg)**	**2 weekly yield range (kg DM/ha)**	**4 weekly yield range (kg DM/ha)**
		Min - Max	**Min - Max**
1(LFLFM)	17.0	33 - 458	49 - 1160
2(LFNFM)	9.0	27 - 361	43 - 952
3(LFLFL)	11.9	21 - 356	37 - 978
4(LFNFL)	9.2	18 - 348	51 - 595
5(HFNFL)	14.2	66 - 1052	160 - 1671
6(HFHFM)	32.4	68 - 959	134 - 2074
7(HFHFL)	59.3	151 - 1940	341 - 2897

The 4 weekly harvesting regime was designed so that a harvesting event takes place every 2 weeks by overlapping each 4 week interval. This means that for every second 2 weeks of a 4 week interval, there is a corresponding 2 weeks of new growth, measured as a 2 weekly harvesting event. Each 2 weekly harvestable yield ($Y_{(2w)}$) is then used as the amount of pasture mass standing as cover (Y, Equation 6.8), from which the second 2 weeks growth (2-4 weeks) is grown from, thus providing data to estimate the parameters of the logistic growth curve (Equation 6.11).

Assuming that pasture mass produced as harvestable yields in the first 2 weeks of the 4 week interval ($Y_{(4w)}$), were equal to pasture yield ($Y_{(2w)}$) harvested in the 2 weekly harvesting regime over the same period, *WUE* were then calculated for every two weeks as:

$$WUE = \frac{Y_{(4w)} - Y_{(2w)}}{ET_{a(2nd\text{-}2w)}}$$

Equation 6.11.

where $Y_{(4w)}$ and $Y_{(2w)}$ are the yields from the 4 weekly and 2 weekly harvesting regimes respectively. $ET_{a(2nd\text{-}2w)}$ is the accumulated amounts of ET_a over the second 2 weeks of each 4 weekly interval.

Equation 6.11 calculates *WUE* as an *average* rate which assumes that over a 2 week period, pasture growth is linear with respect to accumulated ET_a. In contrast, the logistic curve described by Equation 6.8, calculates an *instantaneous* rate of water use that is non-linear, as pasture mass that is standing as cover, increases. It is assumed that the average *WUE*, calculated from Equation 6.11 for every 2 weekly period, is equal to the instantaneous rate (dY/dET_a - Equation 6.8) at different levels of pasture masses that were measured as $Y_{(2w)}$). The values from Equation 6.11 can then be used to obtain the best fitted parameters to the efficiency of water use as affected by the amount of pasture mass that is standing as cover (Equation 6.8).

The main assumption of this model is that the ranges of $Y_{(2w)}$ throughout the year (Table 6.1) represents the range of harvestable pasture mass standing as cover over a single growth period. Before discussing the results, it is important to note that these ranges of $Y_{(2w)}$ at each site (Table 6.1) are generally lower than the normal ranges observed over grazing periods longer than 2 weeks. This may place a limitation on the ability of the model to predict yields in instances with longer grazing or harvesting periods. Nevertheless, the emphasis of this study is to develop a model based on biological concepts explaining pasture growth, rather than just obtaining good mathematical fits to field pasture yields. Furthermore, the harvesting regimes and methodology adopted in these field experiments made it possible to calculate *WUE* using Equation 6.11.

6.3.3 **Results**

6.3.3.1 ***Relationships between modelled and observed pasture growth rates***

The fitted quadratic relationships between *WUE* and $Y_{(2w)}$ explained by Equation 6.8 are presented in Figure 6.4a for the seven different sites at Ballantrae. The best fitted parameter values obtained for each site and their coefficients of determination (R^2) are shown in Table 6.2. On average, the model explains 46% of the variation in *WUE* over twenty five harvests at seven sites differing in their soil fertility status. Figure 6.4b shows how the model performs at predicting *WUE* across the full range of sites at Ballantrae. The model explained 54% of the variation in predicted values from those observed around the 1:1 regression line. Using a regression line through the origin, the model could explain 87% of the variation but indicates that the model generally under-predict measured values. Part of the variation in measured *WUE* unexplained by the model are undoubtedly caused by the errors in modelled ET_a values (Fig. 6.2a) for the Ballantrae Station. Differences are known to occur between different slope, aspect, and fertiliser categories (D.Barker, pers. comm.).

Brougham (1955) observed that pasture growth rates were generally at their highest when harvestable pasture masses, standing as cover, were about 2000kg DM/ha due to maximum light interception at these pasture masses. The $Y_{(2w)}$ values shown in Table 6.1 were all lower than 2000kg DM/ha and would therefore, generally fall below the points of maximum average growth (Fig. 6.5a) of the sigmoid curves at all sites. This may explain why the model generally under-estimated the measured *WUE*. As a consequence the $Y_{ceiling}$ values calculated from the $\mathbf{a(ET_a)}$ and **b** parameters, using

Equation 6.9 ranged from 662kg/ha on site 4 (located in the LFNF farmlet) to 2526kg/ha on site 7 (located in the HFHF farmlet) which were much lower than some of the yields that were observed in Chapter Three.

The corresponding $g_{ceiling}$ values calculated using Equation 6.10, ranged from 7.1 to 30.3kg/ha/mm To put these results into perspective, the $g_{ceiling}$ values can be converted into daily growth rates as follows: given average daily ET_a of 0.7 mm in winter and 5.0 mm in summer, the maximum daily increments in yield on a LF site, with $g_{ceiling}$ of 12.0kg/ha/mm for example (site 3), would be 8kg/ha/day and 60kg/ha/day in winter and summer respectively. On a HF site, with $g_{ceiling}$ of 30.3kg/ha/mm, the maximum daily increment in yield would be 21kg/ha/day in winter and 152kg/ha/day in summer (site 7). Brougham (1955) observed maximum daily increments of 168kg/ha/day in spring (the fertility level was not reported).

Table 6.2 Variables and parameter values obtained when the logistic growth at each site is modelled according to pasture mass standing as cover ($Y_{(2w)}$).

Site Number (Location)	**a(ET_a) (kg/kg/mm)**	**b (ha/kg/mm)**	**Adjusted R^2 (%)**	**Calculated $Y_{ceiling}$ (kg/ha)**	**Calculated $g_{ceiling}$ (kg/ha/mm)**
1(LFLFM)	8.0×10^{-2}	8.7×10^{-5}	47	920	18.4
2(LFNFM)	4.7×10^{-2}	4.6×10^{-5}	44	1022	12.0
3(LFLFL)	4.6×10^{-2}	4.4×10^{-5}	66	1045	12.0
4(LFNFL)	4.3×10^{-2}	6.5×10^{-5}	44	662	7.1
5(HFNFL)	4.8×10^{-2}	2.5×10^{-5}	57	1920	23.0
6(HFHFM)	4.0×10^{-2}	2.0×10^{-5}	42	2000	20.0
7(HFHFL)	4.8×10^{-2}	1.9×10^{-5}	25	2526	30.3

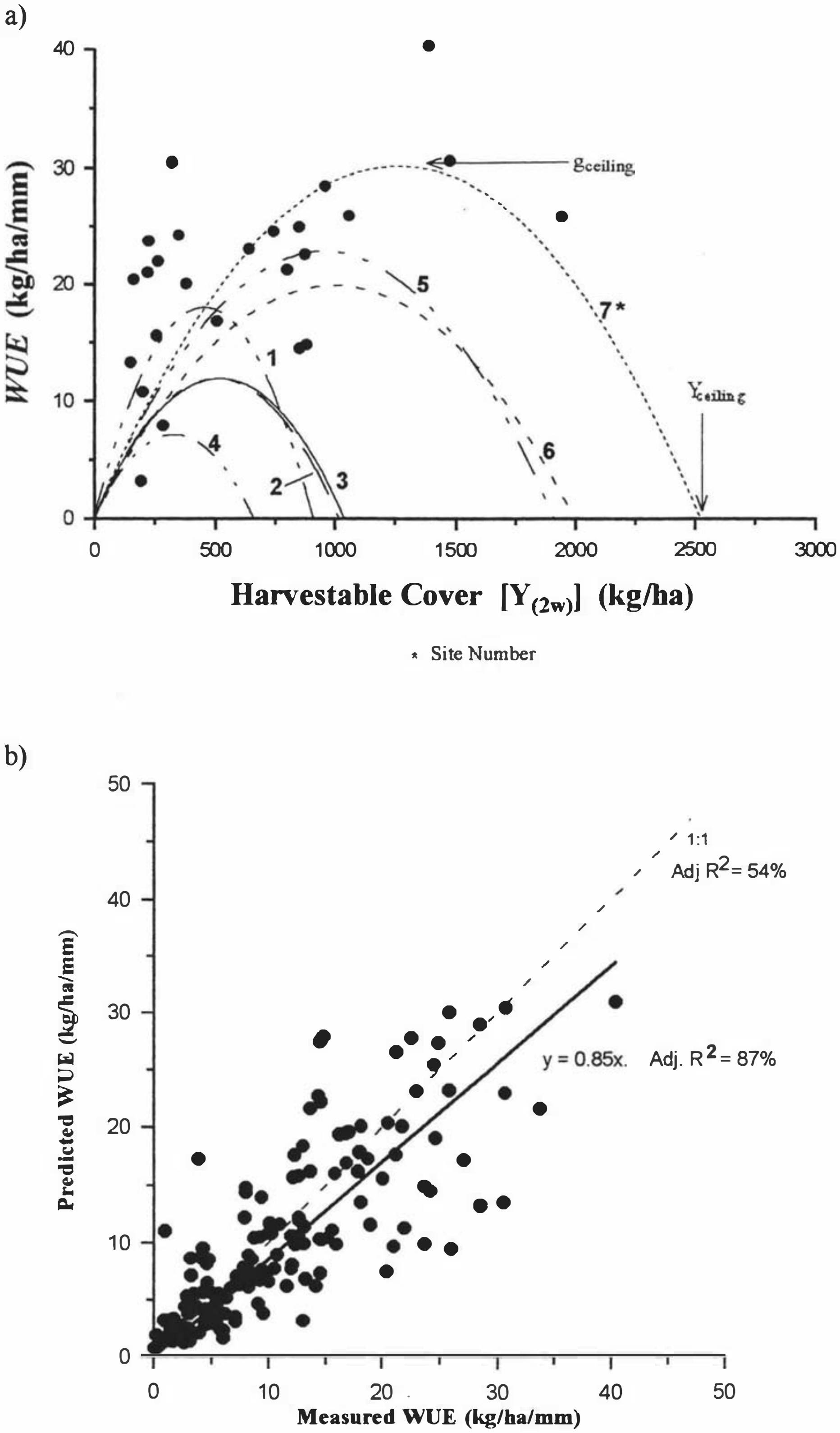


Figure 6.4 a) Logistic growth curves showing increasing in harvestable yield per unit ET_a (*WUE*) as harvestable yield standing as cover ($Y_{(2w)}$), increases. (Plotted points are for site 7 while the regression lines are for all sites).
b) The relationship between modelled and measured *WUE*.

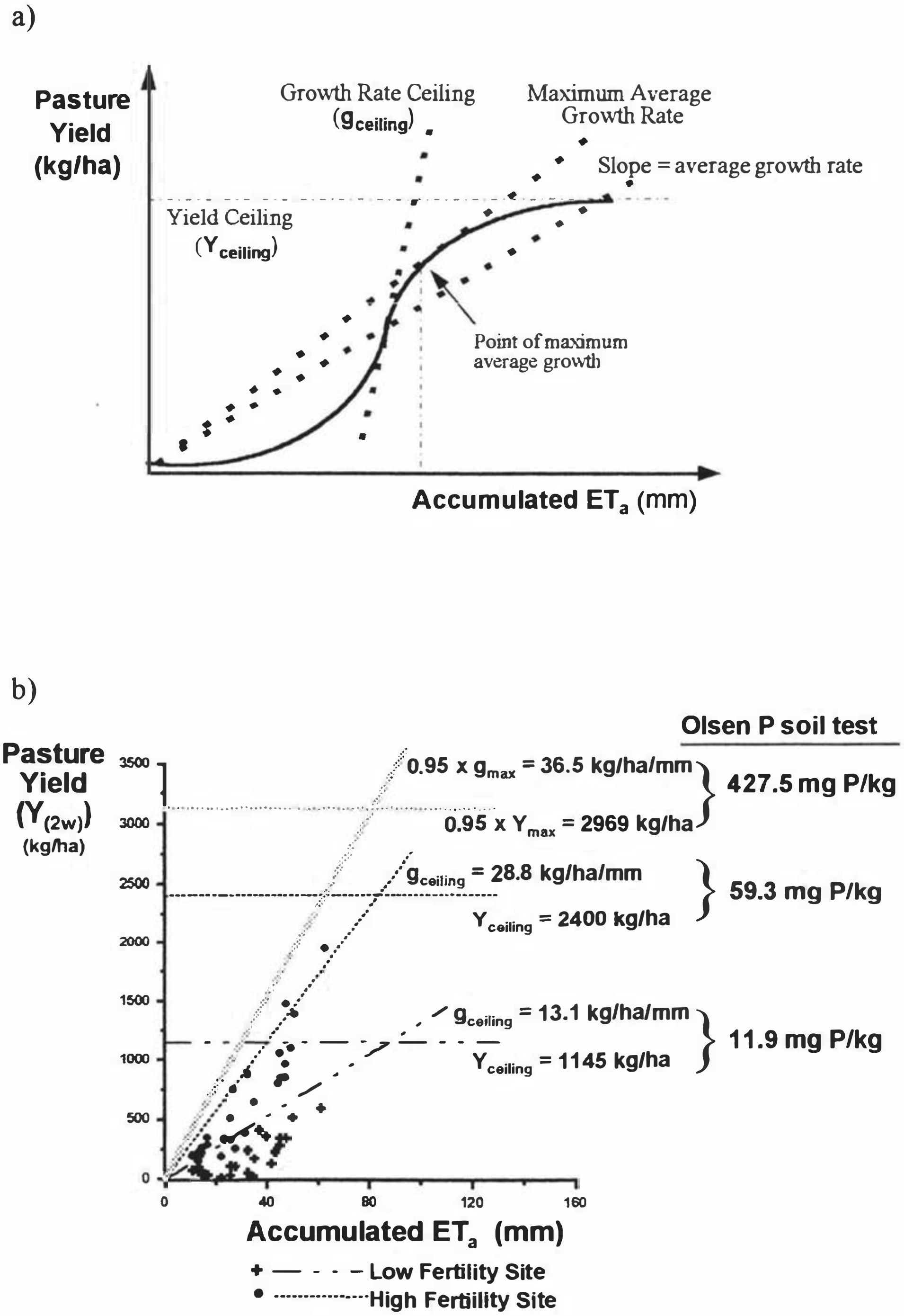


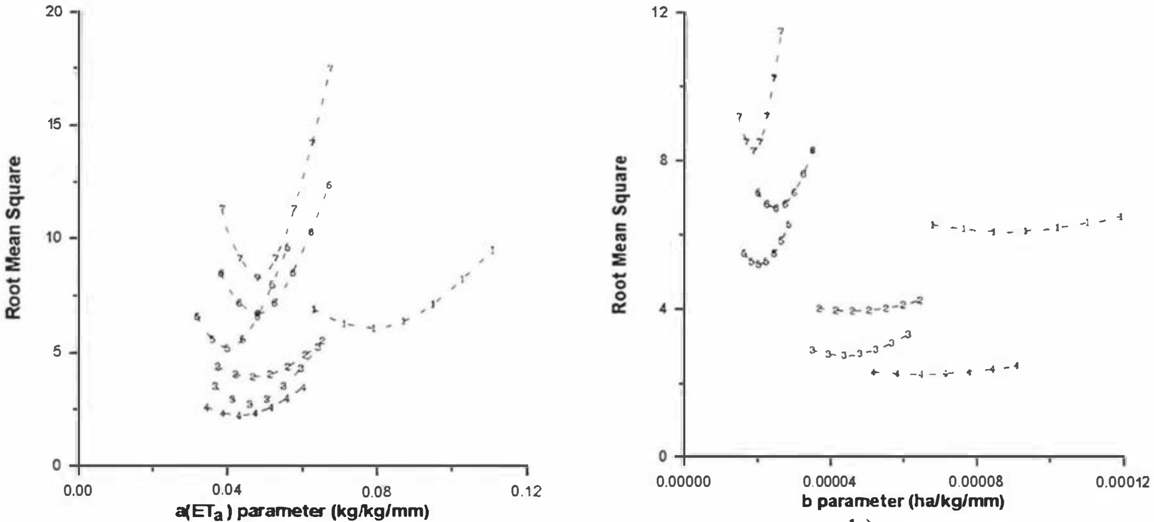
Figure 6.5 a) Theoretical sigmoid growth curve as ET_a accumulates from the beginning of a regrowth period, b) actual values (data points) obtained from sites 3 and 7 using $Y_{(2w)}$ as the pasture mass standing as cover and lines modelled using various $g_{ceiling}$ and $Y_{ceiling}$ values.
(Note: Values shown in b) are slightly different from those in Table 6.2 because the values shown, were predicted from the Michaelis-Menten equation (Eqn. 6.12, section 6.4)).

6.3.3.2 *Sensitivity analysis of the modelled parameters*

The best fitted climatic parameter, **$a(ET_a)$** varied very little from one site to another compared to the **b** parameter (Table 6.2). An exception to this observation is Site 1. This difference is a direct result of the $Y_{(2w)}$ cover yields being lower than expected for the level of fertility at this site (Table 6.1). This site generally had lower water holding capacity and higher C:N ratio than all the other sites due to the lower animal excreta returns imposed by its North West aspect, exposing it to the strong North Westerly prevailing winds (delPino Machado, 1994).

As mentioned earlier (section 6.3.1), the term **$a(ET_a)$**Y of Equation 6.8 represents the net balance between the rate of new growth and the rate of senescence (units of **$a(ET_a)$**: kg/kg/mm). This term is dependent on accumulated ET_a and may not be dependent on soil fertility. This is because, the range of pasture mass existing as cover ($Y_{(2w)}$) (Table 6.1) is already clearly dependent upon the fertility of the soil. However, it is linear to pasture mass existing as cover according to **$a(ET_a)$**. The term **b**Y^2 on the other hand, represents the damping of growth due to self shading within a sward canopy (units of **b**: ha/kg/mm). This term is non-linear with pasture mass existing as cover. It is dependent on the fertility of the soil but not dependent on accumulated ET_a.

In assessing the effect of changes in the values of **$a(ET_a)$** and **b** parameters that would affect the calculated $Y_{ceiling}$ and $g_{ceiling}$ of each site, the root mean square (RMS) (eg., Equation 6.7) of the magnitude of the observed and computed *WUE* values was used as the criterion for testing the sensitivity of each parameter to change. Figures 6.6a, and b show the variations in RMS when each parameter was varied in 10% increments The results show that the high fertility sites are more sensitive to changes of these parameters than the low fertility sites. This was expected as the $Y_{(2w)}$ data at the low fertility sites had more points around and above the point of maximum average growth on the sigmoid curve (Fig. 6.5a) than the high fertility sites. This reflects the period of rapid exponential growth being more sensitive to change in parameter values than growth during the initial lag phase of the growth curve (Fig. 6.5a).



a) b)

Figure 6.6 Effects on Root Mean Square (e.g., Equation 6.7) by varying the best fitted a) **a(ET$_a$)** and b) **b** parameters by 10%. The points are labelled according to the number of the site.

6.3.4 Discussion

The construction of this model was based on describing real patterns of pasture growth as observed by Brougham (1955). Figure 6.4a shows pasture growth increasing in efficiency with each increment of ET$_a$, up to a certain amount of harvestable pasture mass standing as cover, where growth rate is at a maximum ($g_{ceiling}$), after which the rate slows down again until a yield ceiling ($Y_{ceiling}$) is reached where the climatic growth rate is zero. Figure 6.5a shows a theoretical diagrammatic representation of this pattern of increase in yield with increase in accumulated ET$_a$.

The fitted model and the parameters included, is capable of making computed pasture growth sensitive to changes in climate through changes in daily ET$_a$ and to changes in soil fertility. The sensitivity of the model to changes in soil fertility impact mostly through differences in the range of measured pasture masses ($Y_{(2w)}$ in Table 6.1), which are also used to calculate the efficiency of water use (Equation 6.11). At the different ranges of $Y_{(2w)}$ data measured, the parameters **$a(ET_a)$** and **b** were more sensitive at the high fertility sites compared to the low fertility sites.

Each site showed different levels of calculated $Y_{ceiling}$ and $g_{ceiling}$ (Figure 6.4a). These levels are mostly due to the differences in the fertility of the soil as affected by fertiliser history, topography and aspect of the trial sites, from which data were collected. For farm management purposes, it will be of vital importance if these calculated $Y_{ceiling}$ and $g_{ceiling}$ values could be predicted from the fertility of the soil, represented by a soil test. This is investigated in the next section.

6.4 MODELLING THE DEPENDENCY OF PASTURE YIELDS AND PASTURE GROWTH RATES ON SOIL FERTILITY: SOIL FERTILITY-WATER USE MODEL.

To model the dependency of $Y_{ceiling}$ and $g_{ceiling}$ values on the fertility of soils, the Olsen P soil test is used to indicate the level of fertility of the soils. Although they were located in the same farmlets, the 1990/1992-Ballantrae Trial sites had a different range of Olsen P values (Table 4.1) compared to the 1993-Ballantrae Trial sites (Table 6.1). Pasture yield and Olsen P data from the 1993-Ballantrae Trial sites will be used to build the model, which will be used to predict pasture yields from the 1990/1992-Ballantrae Trials using their Olsen P values.

6.4.1 **Model Description**

The rate at which an ionic solute gets absorbed through the cell membrane of a plant root, is dependent on its concentration in soil water, which is its medium of transport. This relationship is not linear but follows an asymptotic curve (Epstein and Hagen, 1952). It follows that if the *WUE* is proportional to the amounts of ionic solutes (nutrients) contained in the medium, then the relationship between pasture yield and the ability of the soil to supply nutrients to the medium, must also follow asymptotic curves.

Epstein and Hagen (1952) have linked the process of carrier mediated transport of an ion across a membrane to the enzyme mediated catalysis of a substrate. The ion absorbed has been compared with the substrate, and the carrier with the enzyme. Michaelis-Menten kinetics have therefore been applied to plant ion uptake processes, which is the approach taken here. For the development of the model, it is assumed that the difference in fertility of the sites may be adequately represented through the Olsen P soil test.

The Michaelis-Menten curve is expressed as:

$$Y_{ceiling} = \frac{Y_{max}\,F}{f_{1/2(y)} + F}, \qquad g_{ceiling} = \frac{g_{max}\,F}{f_{1/2(g)} + F}$$

Equation 6.12

where Y_{max} is the maximum yield obtainable when not constrained by soil fertility, g_{max} is the maximum growth rate that is not constrained by soil fertility, F is the soil fertility level measured as the Olsen P test, $f_{1/2(y)}$ and $f_{1/2(g)}$ are the levels of soil fertility to obtain 50% of Y_{max} and g_{max} respectively.

To prove that ceiling yield ($Y_{ceiling}$) is independently related to soil fertility and that effects of climate have been incorporated into the model by the use of ET_a instead of time, the soil fertility level at which 50% of Y_{max} is obtained should be equal to that at which 50% of g_{max} is obtained, i.e., $f_{1/2(y)} = f_{1/2(g)}$. Rearranging the equation so that $(f_{1/2} + F)/F$ are on the left hand side ($f_{1/2}$ represents both $f_{1/2(y)}$ and $f_{1/2(g)}$), it can be shown that for each level of fertility, F, the ratio of the maximum yield (Y_{max}), to the $Y_{ceiling}$, is equal to the ratio of the ceiling growth rate ($g_{ceiling}$) to the maximum growth rate (g_{max}), ie.,

$$\frac{Y_{ceiling}}{Y_{max}} = \frac{g_{ceiling}}{g_{max}}$$

Equation 6.13.

If $f_{1/2(y)} = f_{1/2(g)}$. and Equation 6.13 holds, it implies that $g_{ceiling}$ values as affected by increasing Olsen P values, should approach g_{max} at the same rate as $Y_{ceiling}$ values approaches Y_{max}.

It is important to emphasise that $Y_{ceiling}$ and $g_{ceiling}$ are the ceiling yields and ceiling growth rates possible at each level of Olsen P, while Y_{max} and g_{max} are the *maximum of ceilings* or the potential amount of yield obtainable during each growth period with non-limiting soil fertility (non-limiting Olsen P).

6.4.2 **Results**

From the 1993-Ballantrae Trials data, the Y_{max} and g_{max} values estimated using Olsen P values in the Michaelis-Menten relationship above (Equation 6.12), were 3686 kg/ha and 40 kg/ha/mm respectively (Fig. 6.7). The Olsen P levels where the ceiling values are 50% of Y_{max} and g_{max} were 28 and 22 mgP/kg soil, using $Y_{ceiling}$ and $g_{ceiling}$ values respectively. Given the level of unexplained variation in the $Y_{ceiling}$ and $g_{ceiling}$ values (Fig. 6.7), a difference of 6 Olsen P between $f_{1/2(y)}$ and $f_{1/2(g)}$. may be considered as insignificant. This suggests strongly that Equation 6.13 holds and that the effects of climate have already been incorporated into the model by the use of ET_a. This also provides evidence that $Y_{ceiling}$ is independently related to soil fertility. From here on, $f_{1/2}$ will be used to represent both $f_{1/2(y)}$ and $f_{1/2(g)}$.

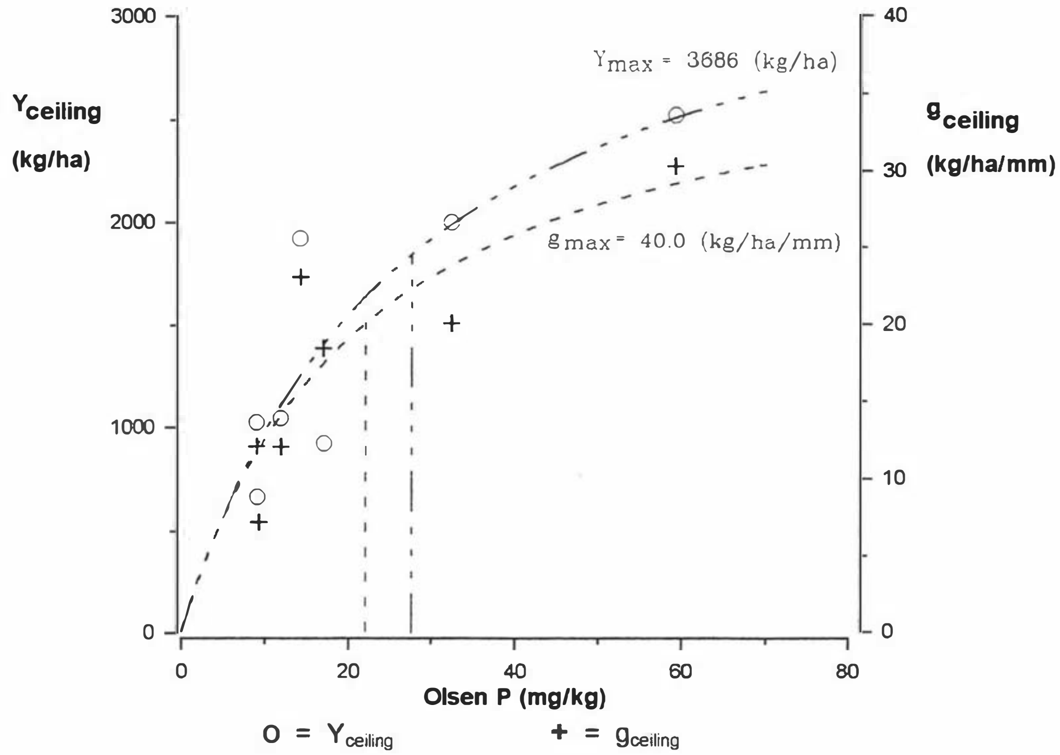


Figure 6.7 The Michaelis-Menten type dependency of yield ceilings and growth rate ceilings on Olsen P for the seven sites at the 1993-Ballantrae Trials. Equations of best fitted regression lines:

$Y_{ceiling} = (3685.7 \times F) / (28 + F)$ (Adj. $R^2 = 68.6\%$)
$g_{ceiling} = (40.0 \times F) / (22 + F)$ (Adj. $R^2 = 68.7\%$)

6.4.3 Discussion

For the purpose of estimating the quantity of fertilisers necessary to correct nutrient deficiencies and obtain maximum economic returns from investment on fertilisers, this model is believed to be superior than the static models that uses Mitscherlich type funtions to describe the relationships between RY and soil test values. Firstly, it is established by these results that a single parameter ($f_{1/2}$) value governs both the dependencies of $Y_{ceiling}$ (kg/ha) and $g_{ceiling}$ (kg/ha/mm) on the fertility of soils (measured as Olsen P). As $g_{ceiling}$ is a function of accumulated ET_a which depends on time, this model is therefore, a *dynamic* model that is dependent on both the changes in climate and on the variations in soil fertility. Secondly, the $f_{1/2}$, parameter in the Michaelis-Menten function which describes the dependencies of $Y_{ceiling}$ and $g_{ceiling}$ on Olsen P values, is measurable as a soil test value. This model is therefore, a *mechanistic* model which is intrinsic of the characteristics of Michaelis-Menten kinetics being applied to plant ion uptake processes. A Mitscherlich type function can also describe the variations in $Y_{ceiling}$ (Equation 4.6 - Best fitted equation: $y = 2685(1 - e^{-0.0441x})$, Adj R^2 = 68.2%). However, the rate constant of -0.0441 is dimensionless with no units that have no biological meaning. It does not demonstrate an understanding of the soil-plant system and is therefore an *empirical* model. As discussed in section 2.5.2, *dynamic* and *mechanistic* models provide better descriptions with understanding of soil-plant systems.

The interpretation however, of the parameter, $f_{1/2}$, for the purpose of fertiliser recommendations, has to be treated with caution, because Y_{max} is estimated from soil P that would have been accumulated over a very long-term. To assume that S and P fertiliser applications will result in unlimited soil S and P supplies (i.e., yields on fertilised plots equals maximum yields), is too gross a departure from reality. For example, the results in Chapter Three showed that the yields from the fertiliser treatments on the lower fertility sites, are generally lower than the yield on the control plot of the highest fertility site (Table 3.3). Therefore, applying fertilisers to a soil with soil fertility level of $f_{1/2}$ at high rates (above recommended maintenance rates), will not mean that yields will be increased by 50%. Instead, $f_{1/2}$ should be interpreted as an indication of how fast Y_{max} and g_{max} are approached, i.e., the lower $f_{1/2}$, the faster Y_{max} is approached. This characteristic is similar to that of the rate constant in the Mitscherlich type models, defining the rate of approaching the plateau.

Caution should always be taken when extrapolating beyond measured data points using asymptotic functions. For example, the highest soil fertility level measured as Olsen P in this series of trials was 59.3. This was measured at a site that regularly received a high application rate of SSP fertiliser over 18 years. This model predicts that this site will produce only 70% of Y_{max}. Traditionally, Olsen P test values at which 90-95% of the yield plateau, using Mitscherlich type functions, are considered to be near optimum sites that are non-responsive to further phosphate addition. Using the Mitscherlich type function to describe the relationship betwen $Y_{ceiling}$ and Olsen P values, this same site with an Olsen P of 59 achieved 93% or 68 Olsen P to achieve 95% of Y_{max}. This is compared to an Olsen P of 427.5 needed to achieve 95% of Y_{max} (Fig.6.5a) when using the Michaelis-Menten function (Equation 6.12). This level of Olsen P is only possible to obtain with very high rates of fertiliser application over many years. While such levels have been recorded for some horticultural soils (Hedley M.J., pers. com.), it would be totally uneconomic for pastoral systems to consider operating at these levels. While both the Mitscherlich and the Michaelis-Menten equations give similar descriptions of the variations in the relationships between pasture yields and Olsen P values, the Michaelis-Menten is preferred in this study because of the intrinsic value of $f_{1/2}$ as an indicator of responsiveness. This is despite the Mitscherlich equation predicting 95% of Y_{max} and g_{max} occurring at Olsen P values closer to real farm values in this study (9-59 Olsen P).

The approach taken in the development of this *dynamic* and *mechanistic* model is to provide understanding of the soil-plant system so that pasture growth can be simulated to ultimately predict actual yields (next chapter). Reporting an Olsen P value at which 95% of Y_{max} occurs, has no practical value for this purpose.

6.5 GENERAL DISCUSSION

The models developed in this chapter are very simple but contain key principles that are needed for pasture fertility management. This mechanistic approach is an improvement on the static soil test approach (Chapter Five), because actual pasture yields can be predicted for a certain level of soil fertility with a given set of climatic conditions. However, while the structure is considered superior, the yields predicted over the whole growing season of one year are much lower than expected. For example, the $Y_{ceiling}$ values estimated in Figure 6.4a are much lower than those that were observed in the field at the 1990/1992-Ballantrae Trials where pasture yields of about 5000-7000kg/ha were observed on the HFHF sites during spring 1990 and spring 1991 (Chapter Three). Yield ceilings of about 7000kg/ha or above had been expected at the HF farmlets. The lower yield ceiling values of 893 - 2265kg/ha predicted by the model at site 2 in the LFNF farmlet, to site 7 in the HFHF farmlet, reflect the weaknesses of the data set from which it was developed.

As shown in Figure 6.4a, the number of data points around the maximum climatic growth rates ($g_{ceiling}$) are very few. This is because the only data available for pasture mass standing as cover, were those obtained after 2 weeks growth only. The maximum $Y_{(2w)}$ value measured and used as standing cover in this model, was only 1940kg/ha (Table 6.1). Brougham (1955) showed that maximum growth rates are achieved after about 4 weeks of regrowth, corresponding to about 2000kg/ha of harvestable yield, standing as cover. Therefore, the levels of pasture mass measured as $Y_{(2w)}$, are at levels where the instantaneous growth rates are all near maximum. As there are only a few data points above this level of yields, the non-linear term, $\mathbf{b}Y^2$, which models the damping of growth due to self-shading, forced the model to decrease growth rates faster than in a real system.

In the future, it is recommended that data sets from 6 and 8 weekly harvesting regimes be included to give better representation of pasture yields standing as cover, to obtain better estimates of $Y_{ceiling}$ and $g_{ceiling}$. As Black (1992, p.12) commented, “The basis of action can always be improved by further research, but the data at hand are the best available at the moment.”

CHAPTER SEVEN

A PASTURE GROWTH SIMULATION MODEL

7.1 INTRODUCTION

While it is impossible to predict future weather conditions, the farmer can conduct economic risk assessments with more efficiency, if future actual yields can be predicted according to likely weather scenarios that are derived from historic climatological records for the area. Therefore, simulation models that predict pasture growth forward in time based on some given initial conditions, would be valuable management tools. In Chapter Six, a Water-Use model (section 6.3), was developed to explain the dependency of pasture growth on the amount of available and the harvestable pasture mass standing as cover on a daily basis. Available water was estimated as ET_a and derived from a Soil Water Balance model (section 6.2). The data used in the development of the Water-Use and the Soil Water Balance models were those collected from the 1993-Ballantrae Trials. In this chapter some initial conditions are estimated for each fertility level using soil test values in the Soil Fertility-Water Use model (section 6.4). These parameter values are used to simulate pasture growth through time using climatological data during 1990 to 1992 to predict harvested yields in the 1990/1992-Ballantrae Trials (Chapter Three). In addition, these parameter values obtained at Ballantrae are examined to see if they could be transferred to other sites with different soils and climates to Ballantrae.

The reliability of a simulation model is based on its structural and mechanistic validity, ie., a model should not only match the observed results, but also reproduce the structure and mechanisms of the real system that produces those results. The structural and mechanistic characteristics of the models to be simulated here, were illustrated in the previous chapter. Close matches were obtained between predicted soil water contents and those observed (Fig. 6.2a) indicating that the model reliably estimates ET_a. In addition, predicted ceiling pasture yields and ceiling growth rates were strongly correlated with indices of soil fertility (Fig. 6.6). Both parameters of yield (units: kg/ha and kg/ha/mm) approached their maximum values at the same rate when defined by the parameter $f_{1/2}$.

However, as discussed in section 6.5, using $Y_{(2w)}$ data as the pasture mass standing as cover, does not provide a data set which represents the levels of pasture mass at which damping of growth due to self-shading would take effect. Consequently, $Y_{ceiling}$, the ceiling yield, and $g_{ceiling}$, the ceiling growth rate for each fertility level are poorly defined by the data available and are likely to be under-estimated because of this limitation in the data set.

The objectives of this chapter are, i) to find better estimates of the parameter values than the ones obtained from the $Y_{(2w)}$ and $Y_{(4w)}$ data sets that were used for the development of the model in Chapter Six, ii) to use these parameter values to simulate pasture growth during variable time intervals (ranged from 4 to 9 weeks), for the 1990/1992-Ballantrae Trials (Chapter Three), iii) to investigate if the same parameter values used to predict harvested yields at Ballantrae, can be transferred to predict yields at other sites from the lower North Island.

7.2 METHOD AND RESULTS

A simplified Flowchart of the simulation model is presented in Figure 7.1. Using the soil fertility-water use model (Equation 6.12), the ceiling yields and ceiling growth rates for each soil fertility level can be predicted. From these ceiling values, the relative pasture growth rate **$a(ET_a)$** and the damping of pasture growth **b** parameter values (Equations 6.9, 6.10) could then be estimated for each soil fertility level (F), as indicated by the Olsen P test value. Daily increments of growth as affected by the harvestable pasture mass standing as cover, and the daily amount of ET_a, are then computed. It is assumed that daily increments of pasture growth are linearly related to the daily amount of ET_a, according to the growth rate for the pasture mass standing as cover at the beginning of each day. The new growth rate re-calculated at the end of the day, which will be used to calculate the increment of growth for the next day, takes into account the non-linear damping of growth due to self-shading (Equation 6.8).

7.2.1 Using Olsen P as the Indicator of Soil Fertility to Estimate Initial Parameter Values

As mentioned above, the $Y_{ceiling}$ and $g_{ceiling}$ values of each fertility level, were under-estimated using the $Y_{(2w)}$ and $Y_{(4w)}$ data sets (section 6.5). Consequently, values of Y_{max} and g_{max}, the maximum yield and maximum growth rate obtainable when all the constraints placed by fertility level are removed, were also under-estimated. Thus, when those values (section 6.4.2) were used for simulation of pasture growth during periods longer than 4 weeks (1990/1992-Ballantrae Trials, Chapter Three), the predicted harvested yields were much lower because for each fertility level, estimated $Y_{ceiling}$ were much lower than yields observed. Higher estimates of Y_{max} and g_{max} were therefore, required to achieve realistic predictions of harvested yields, when the harvest (or grazing) interval exceeds 2 weeks.

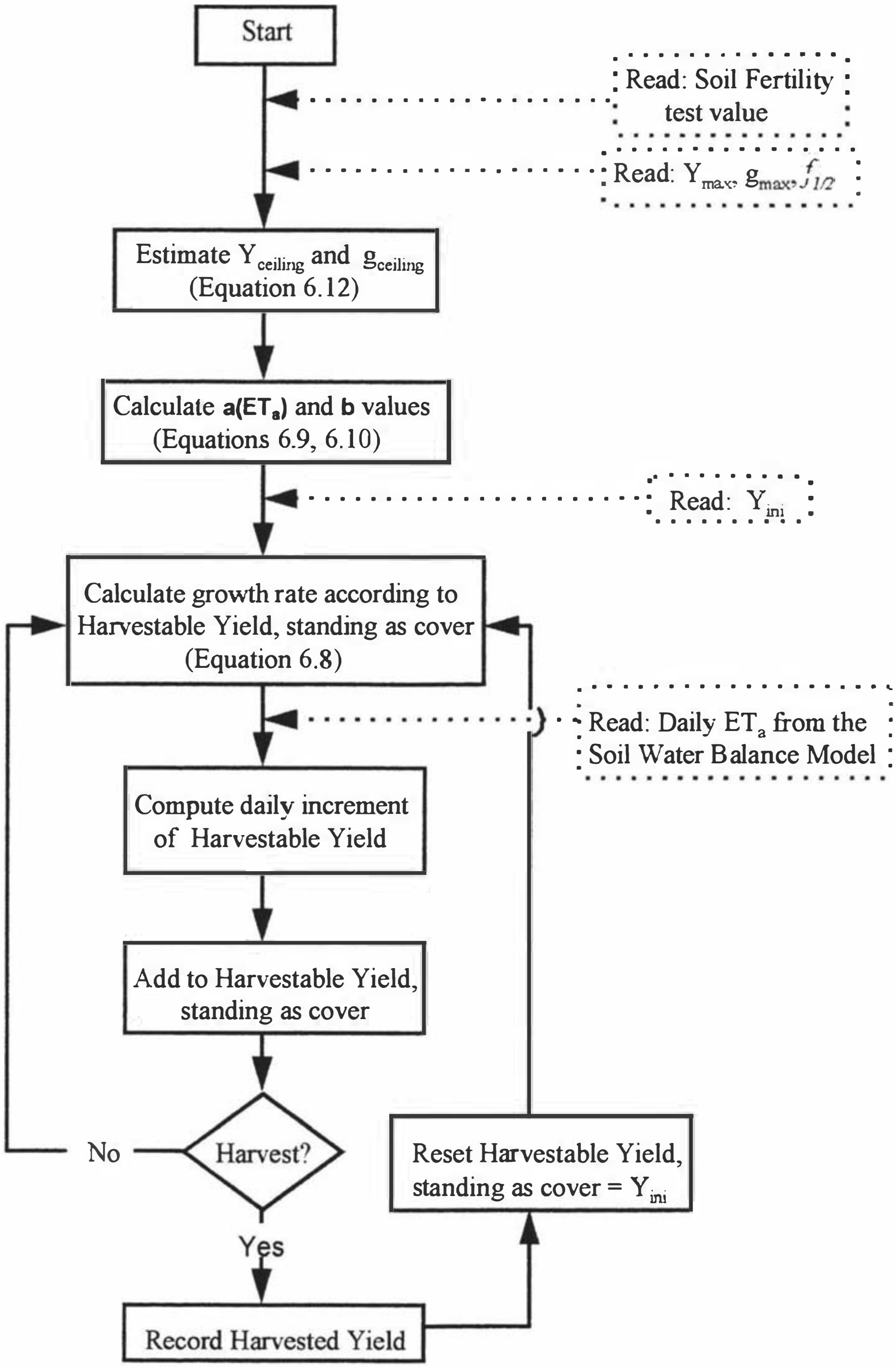


Figure 7.1 Flowchart of a pasture simulation model for different levels of soil fertility and driven by actual evapotranspiration (ET_a), computed from climatological data.

7.2.1.1 *Y_{max} and $f_{1/2}$*

In this section, a more realistic representation of Y_{max} is estimated from the yields measured at the eleventh harvesting event ($Y_{(cut11)}$), following growth over the interval 19 November 1991 to 24 January 1992 of the 1990/1992-Ballantrae Trials. 253mm of ET_a was accumulated during the nine weeks of this growth period. This amount of accumulated ET_a was considered to produce near $Y_{ceiling}$ yields at each site in the 8 fertility regimes. These measured $Y_{ceiling}$ were used to estimate Y_{max}.

Figure 7.2 shows the regression between $Y_{(cut11)}$ ($\equiv Y_{ceiling}$) and Olsen P values, using Equation 6.12. The values obtained were 8923kg/ha for Y_{max} and 14mg P/kg soil Olsen P for $f_{1/2}$.. This Y_{max} value appears more realistic than 3125kg/ha obtained, using the $Y_{ceiling}$ values estimated from the $Y_{(2w)}$ data set (Fig. 6.6). The $f_{1/2}$ value of 14mg P/kg soil Olsen P, also implies that Y_{max} approaches faster with increasing Olsen P, than predicted using the $Y_{(2w)}$ data set which showed an $f_{1/2}$ value of 23mg P/kg soil Olsen P.

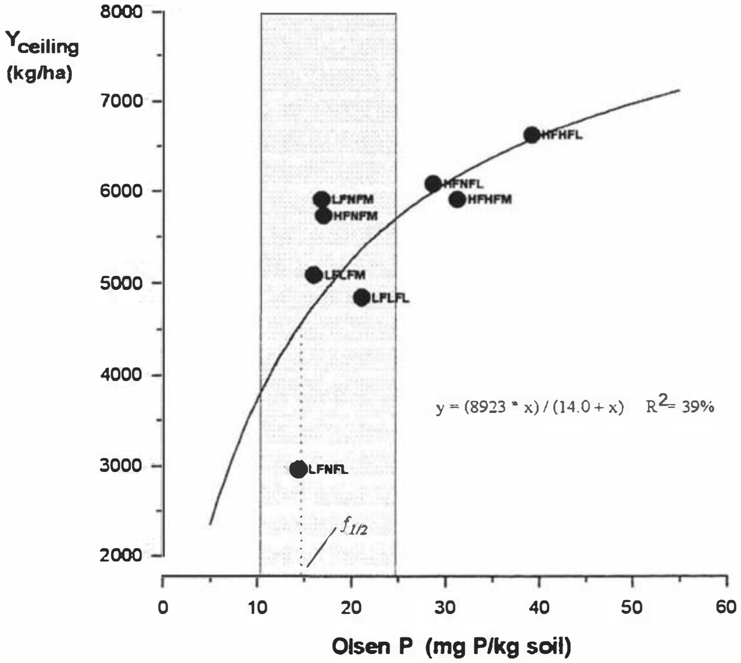


Figure 7.2 The relationship between pasture yield ($Y_{ceiling}$ [$\equiv Y_{(cut11)}$], from 19 Nov 1991 to 24 Jan 1992) and Olsen P. The solid line and equation, represent the best fit of the Michaelis-Menten function (Eqn. 6.12).

7.2.1.2 g_{max}

While Y_{max} could be estimated from a single set of harvested yields, as in the previous section, an estimation of the maximum growth rate, g_{max}, requires a population of yields influenced by variable amounts of accumulated ET_a (Eqn. 6.11). For a more realistic estimate of g_{max}, field trials with a series of longer harvest intervals are required. However, it was shown in section 6.4.3, that the $f_{1/2}$ value governing the rate at which the $g_{ceiling}$ values approach g_{max} with increasing Olsen P, is equal to the rate in which $Y_{ceiling}$ approaches Y_{max} (Fig. 6.6 and Eqn. 6.13). Knowing this, it is possible to approximate a realistic value of g_{max} without a comprehensive $g_{ceiling}$ data set using the same $f_{1/2}$ obtained for the relationship between $Y_{ceiling}$ and Olsen P values.

Brougham (1959) observed maximum daily growth rates of about 170kg/ha/day but no fertility level was reported. If it is assumed that this growth rate was observed at a medium fertility site, then maximum daily growth rates of up to 200kg/ha/day can be expected on a HF site. This growth rate is the same as 44kg/ha/mm, assuming that it was observed on a typical spring day with 4.5mm of ET_a (section 6.2.2).

It is important to keep in mind that Y_{max} can only be achieved at very high Olsen P values. For example, 90% of Y_{max} of 8923kg/ha in Figure 7.2 is achieved at 126mg P/kg soil Olsen P. On the other hand, the estimated $Y_{ceiling}$ value for the HFHF$\underline{L}$ site, with an Olsen P of 39.2mg P/kg soil , is 6575kg/ha, or 74% of Y_{max}. According to Equation 6.13, the $g_{ceiling}$ of the HFHF$\underline{L}$ site should therefore, also be 74% of g_{max}. If it is assumed that $g_{ceiling}$ of the HFHF$\underline{L}$ is about 44kg/ha/mm, which is 74% of g_{max}, then using $f_{1/2}$ of 14mg P/kg soil Olsen P, g_{max} values of about 60kg/ha/mm can be expected. For experimentation with the model, values of 50, 60, and 70kg/ha/mm were investigated as approximations of g_{max} (Fig. 7.3).

7.2.1.3 Y_{ini}

The final and perhaps the most difficult parameter to estimate is the initial amount of pasture mass from which growth starts. Traditionally, simulation models use total above ground pasture mass at time = 0 (t_0), as starting points for calculations (eg., Morley, 1968; McCall *et al.*, 1986). These estimates are very rough because data for total above ground post-grazing pasture masses are very variable and difficult to measure. For example, at t_0, Morley (1968) used 600kg/ha, while McCall *et al.* (1986) used an estimate of 2000kg/ha. At Ballantrae, total above ground pasture mass after pre-trimming to 5cm heights, range from about 800 to 2000kg/ha in the LF to HF sites respectively (Dr. A.D. Mackay, pers comm.). In this study, growth rates are calculated on the basis of the amount of harvestable pasture mass only, instead of total above ground pasture mass. Estimates of Y_{ini} are therefore, also restricted to harvestable pasture mass.

To estimate Y_{ini}, it is considered that an equilibrium exists between root weight and shoot weight of pasture plants, at various stages of pasture growth (Brower, 1983; Wilson, 1988). At each harvesting event, it is assumed that this equilibrium is offset. The philosophical approach here is that, in order for the sward to be sustained, the re-establishment of the equilibrium between root weight and shoot weight which was offset by a harvesting event, must favour replacing the removed shoots (harvestable pasture mass). Therefore, despite accumulated ET_a being zero at the end of a harvesting event, there will always be an initial harvestable pasture mass, Y_{ini}, that will be contributing to the yield of the next harvesting event, which is independent of the accumulated ET_a of the next harvesting period.

The interest of this study is not to define the theoretical basis of plant behaviour, rather a model will be useful here if observed data from the field study are consistent with a model that is developed from sound concepts. Information on the effects of a harvesting/grazing event on the equilibrium between root weight and shoot weight does not appear to be currently available. However, Troughton (1956) reported a model that shows a linear relationship between the logarithmic of shoot weight and logarithmic of root weight with the slope, *k*, being the sensitive indicator of ratio of root growth to shoot growth. Troughton (1956) found that *k* changes with factors such as nutrient supply and the stage of plant development (eg., there is a decrease in photosynthate allocation to roots while flowering). Davidson (1969) gave a formal statement of variations in *k* as:

$$\text{root mass} \times \text{rate of nutrients absorption} \;\; \alpha \;\; \text{leaf mass} \times \text{rate of photosynthesis.}$$

Therefore, immediately after harvesting, it is obvious that the product of root mass and rate of nutrient absorption must exceed the product of leaf area and rate of photosynthesis because the leaf mass is dramatically reduced during harvesting. Thus, when equilibrium is re-established, it is proposed that an initial harvestable yield, Y_{ini}, of up to 200kg/ha can exist, to ensure that the sward will be sustained.

It is believed that an upper boundary of 200kg/ha ($< 2\%$ of Y_{max}) for Y_{ini} is acceptable, otherwise the model would be obviously unrealistic. Furthermore, an upper boundary of 70kg/ha/mm for g_{max} will naturally restrict Y_{ini} below this value as shown in Figures 7.3a, b, and c.

To estimate acceptable Y_{ini} values, simulations were conducted using Y_{ini} values ranging from 75 to 200kg/ha for g_{max} values of 50, 60, and 70kg/ha/mm, using a Y_{max} value of 8923kg/ha and an $f_{1/2}$ of 14mg P/kg soil Olsen P. Figures 7.3 a, b, and c show the linear regressions between simulated harvested yields from the HFHFL site in the 1990/1992-Ballantrae Trials (Olsen P = 39.2), using climatological data between autumn 1990 - autumn 1992, and the yields measured on the control plots at the same site during the same period. This site was chosen for experimentation because it had the least residual sum of squares associated with its $Y_{ceiling}$ value from the regression using the Michaelis-Menten function (Fig. 7.2).

Figure 7.3a shows that 50kg/ha/mm is too low an estimate for g_{max}, unless Y_{ini} is increased above 200kg/ha. Using 60kg/ha/mm as g_{max} (Fig. 7.3b) shows that a value of 150kg/ha as Y_{ini} gave the best regression between simulated and measured harvested yields. On the other hand, when 70kg/ha/mm (Fig. 7.3c), was used as g_{max}, a value of 100kg/ha as Y_{ini} gave the best regression between simulated and measured harvested yields. It is preferred that Y_{ini} is kept at a minimum. Therefore, the values of 70kg/ha/mm and 100kg/ha were chosen for g_{max} and Y_{ini} respectively.

The initial values recommended for simulation of yields at different sites with different fertility levels are summarised in Table 7.1.

Table 7.1 Summary of initial parameter values estimated from the Olsen P test.

Parameter	Initial Value
Y_{max}	8923kg/ha
g_{max}	70kg/ha/mm
$f_{1/2}$	14.0 Olsen P
Y_{ini}	100kg/ha for HF sites 50kg/ha for LF sites

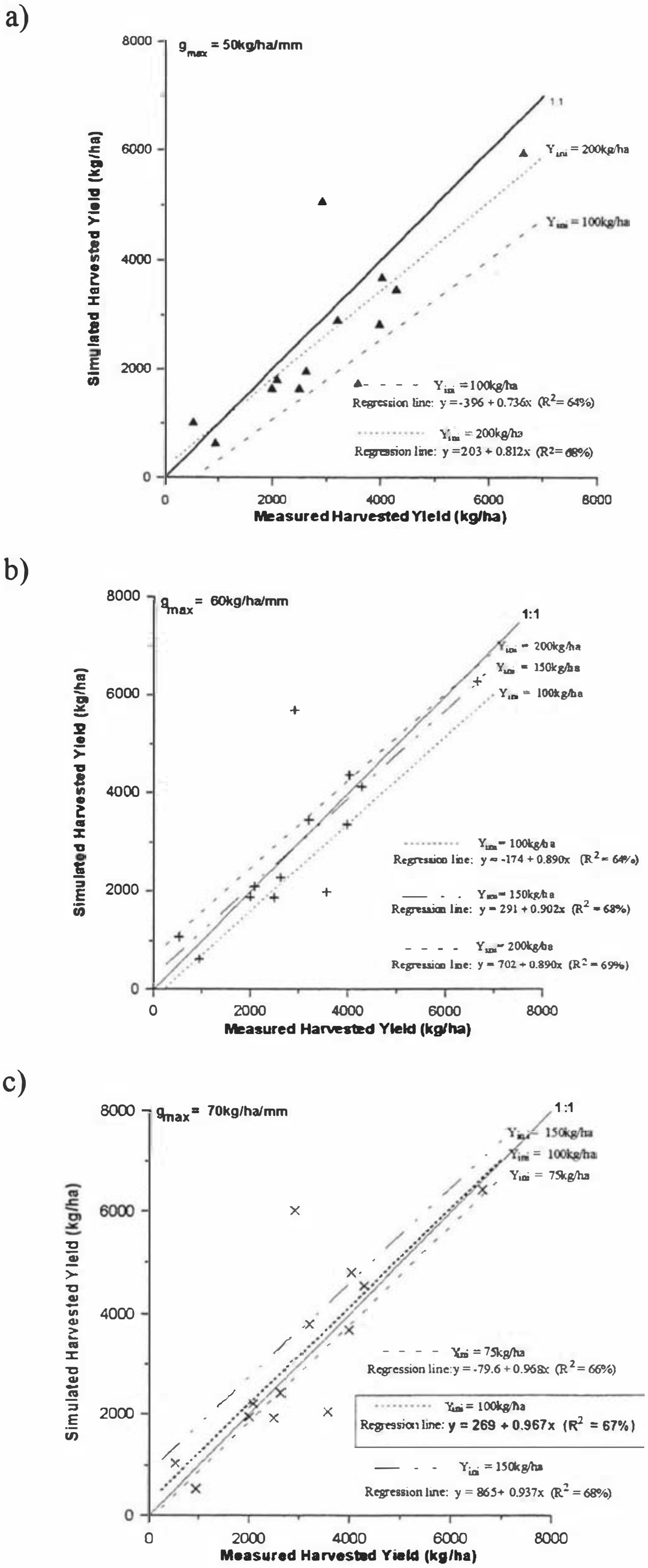


Figure 7.3 Regressions between simulated and measured harvested yields at the HFHFL site, during 1990-1992, at different levels of Y_{ini}, using g_{max} values of:
a) 50kg/ha/mm, data points shown are for Y_{ini} = 200kg/ha,
b) 60kg/ha/mm, data points shown are for Y_{ini} = 150kg/ha, and
c) 70kg/ha/mm, data points shown are for Y_{ini} = 100kg/ha.

7.2.1.4 *Results and Discussion*

Figure 7.4 shows the simulated and measured harvested yields at the HFHFL site, from autumn 1990 - autumn 1992, using the initial values summarised in Table 7.1. In general, the variations in harvested yields predicted by the model, closely resemble the variations in those measured throughout the two years. These results reflect the structural strength of the model, despite its simplicity.

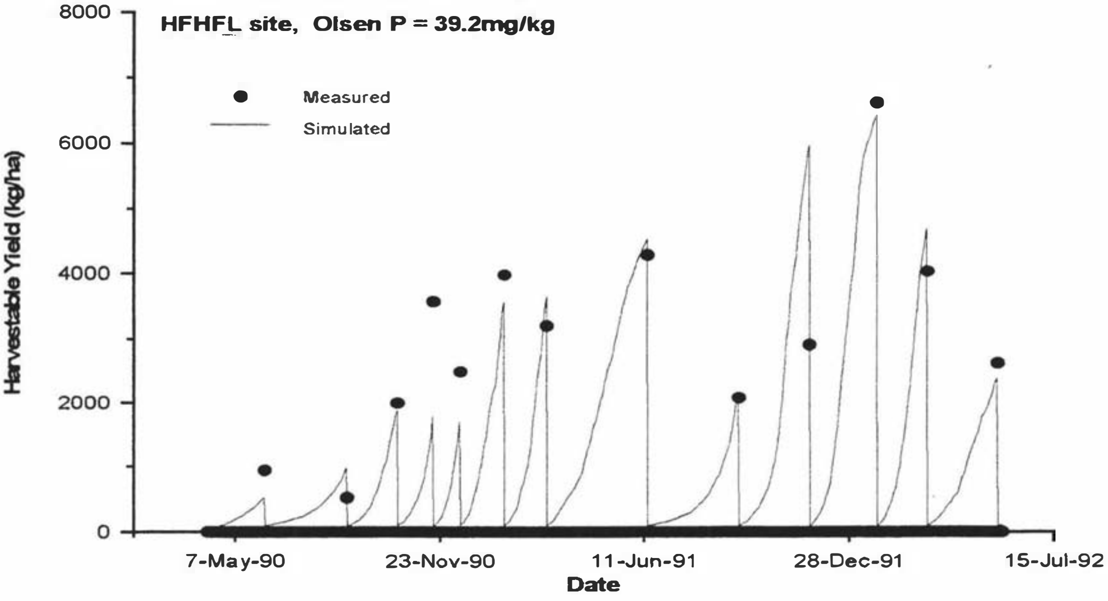


Figure 7.4 Simulated and measured yields at the HFHFL site from autumn 1990 - autumn 1992

When the initial values, summarised in Table 7.1 were used for simulation of pasture growth on the other Ballantrae sites with different Olsen P values from the 1990/1992-Ballantrae Trials, the results showed that these initial values held fairly well for the sites that were located in the HF farmlets (Fig. 7.5).

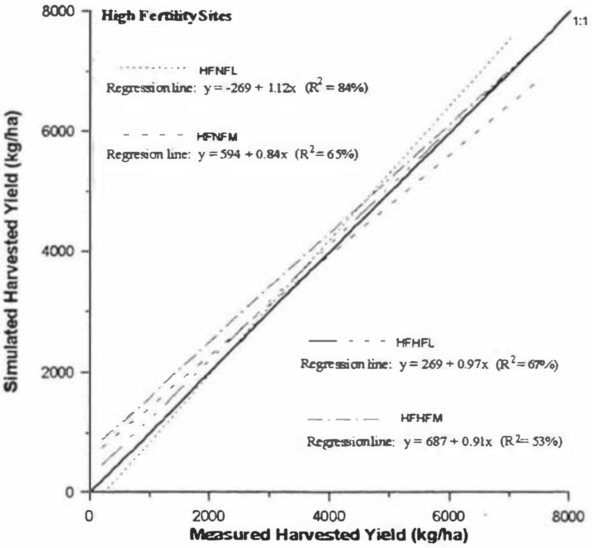


Figure 7.5 Regressions between simulated and measured harvested yields from the sites located on the HF farmlets. (Data points not shown)

However, the same initial parameter values (Table 7.1) generally over-estimated lower pasture yields at the LF sites (Fig. 7.6). Figure 7.7 shows the typical pattern of simulated growth compared to the measured harvested yields observed on the LF sites. The growth trend over time is generally well matched, but the lower harvested yields were over-estimated, particularly during the second year (June 1991 - July 1992).

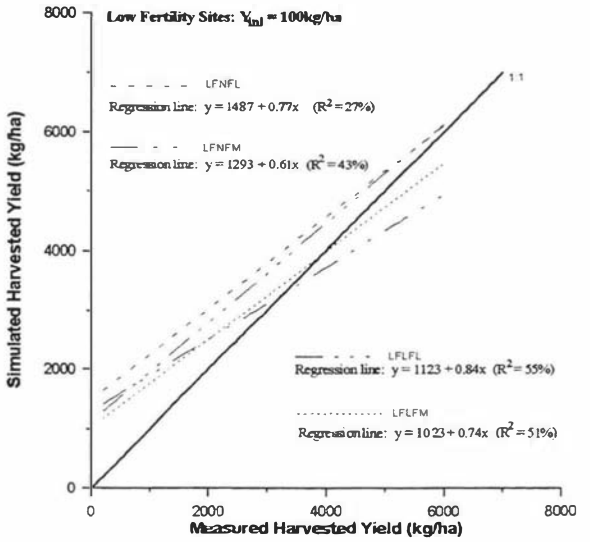


Figure 7.6 Regressions between simulated and measured harvested yields from the sites located on the LF farmlets. (Data points not shown)

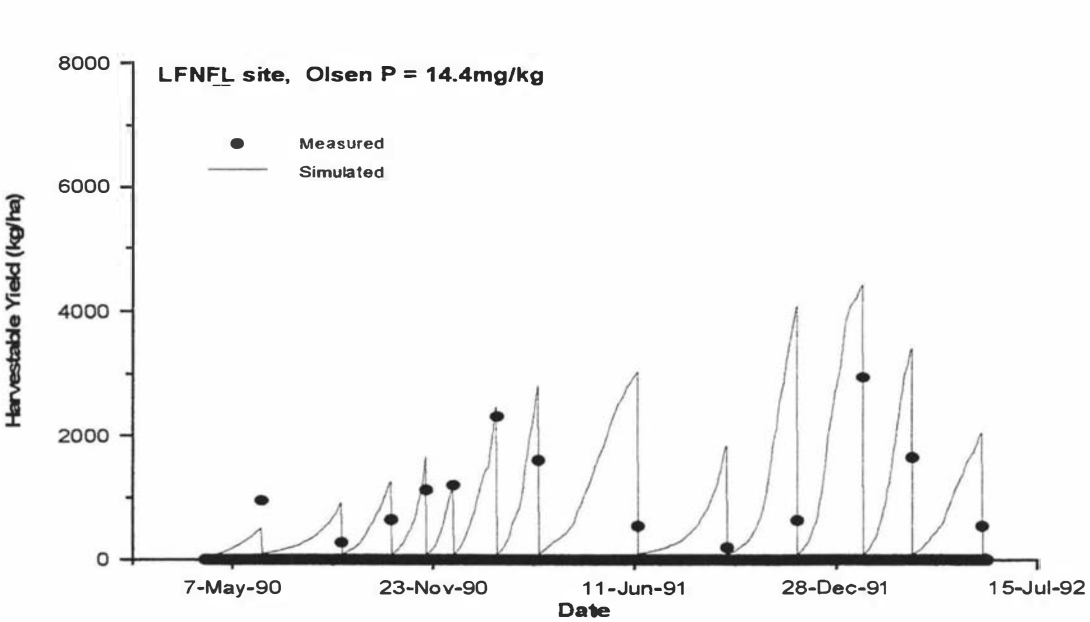


Figure 7.7 Simulated and measured yields at the LFNFL site from autumn 1990 - autumn 1992

The reasons for the model generally over-estimating the harvested yields at the LF sites could be, i) the Y_{ini} value of 100kg/ha is over-estimated for these LF sites, or ii) using Y_{cut11} as the data set to represent $Y_{ceiling}$ value for each site is not reliable, or iii) the soil fertility-water use model (Eqn. 6.12), over-estimated the $Y_{ceiling}$ values (Fig. 7.2) at these sites, ie., $f_{1/2}$ may be too low and the LF sites are approaching Y_{max} and g_{max} too quickly as soil fertility increases.

Firstly, it is very likely that a harvesting event at a LF site does not affect the equilibrium between root weight and shoot weight as much as a HF site, because of the differences in sward types. For example, the clover composition of the LF are generally higher than the HF sites (Table 3.5). When the Y_{ini} value of 50kg/ha was used for the LF sites, the regressions between simulated and measured harvested yields were improved (Fig. 7.8), compared to when a Y_{ini} of 100kg/ha (Fig. 7.6) was used, ie., the regression lines all moved closer to the 1:1 line.

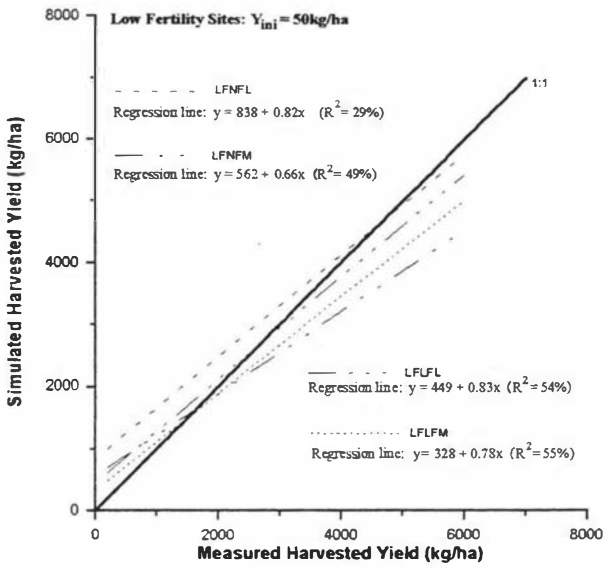


Figure 7.8 Regressions between simulated and measured harvested yields from the sites located on the LF farmlets, using a Y_{ini} value of 50kg/ha. (Data points not shown)

Secondly, during the eleventh harvesting event on 24 January 1992, from which Y_{cut11} were measured, it was observed that grass at the HF sites were still at the vegetative growth stage, while grass at the LF sites were at the reproductive growth stage, despite the lower mass. Although not certain, it is likely that differences in tiller dynamics of the swards with higher herbage mass at the HF sites may contribute to differences in the timing of reproductive tiller formation (Matthew, 1992). Higher herbage mass swards have a lower tiller density due to base shading (Davies, 1988). It is therefore likely, that there is delay in the timing at which the ceiling yield value is reached at each successive fertility level. Consequently, during the eleventh harvesting event, pasture growth rates at the LF sites had reached the asymptotic phase of the sigmoidal pasture growth curve, while they were still on the increase at the HF sites (Fig. 6.5a). Perhaps more reliable estimates of ceiling yields would be achieved using different harvesting intervals that take into account the differences in the timing at which the LF and HF sites reach the asymptote of the growth curve.

Thirdly, the Michaelis-Menten relationship between this pasture yield data and Olsen P soil test, does not give a good explanation of the measured yields in the Olsen P test values between 10 and 25mg P/kg soil (shaded area, Fig. 7.2). Therefore, there will always be some discrepancies in predicting the $Y_{ceiling}$ values of the sites that have soil P status within this range.

The over-estimation of yields in the second year may have been caused by the inhibition of tillering after repeated defoliation which created low plant carbohydrate status (Auda *et al.*, 1966; Davies, 1974).

Nevertheless, the weaknesses of the model due to the lack of data to give proper estimates of the initial parameter values, are believed to be overridden by its stability and structural strength, as indicated by its ability to simulate the patterns of growth that resemble the patterns of measured yields throughout the years. Furthermore, its simplicity, with only four parameters (Tables 7.1) regulating the dependency of pasture growth on climate and fertility, provides a strong basic framework for future research. For example, the model would be unlikely to lose its stability when parameters are added to incorporate other aspects of a grazed pasture system such as sward composition, grazing regimes, and dynamic nutrient status.

7.2.2 **Transferring the Model Away from Ballantrae, to Sites in the Wairarapa.**

To test the stability of the model, it was important to investigate if the parameter values obtained at Ballantrae, would hold for other sites located around the lower North Island having different soil types and climatic conditions.

To develop soil water balances of soil types different from those at Ballantrae, the only soil property required for the soil water balance model, is the field capacity. Including a permanent wilting point soil property in the soil water balance at Ballantrae did not improve the predictions of soil water contents (section 6.2.2), hence, it was not required. Root distribution data would also be required but this data was not available from the other sites, so the root distribution data from Ballantrae was used again in the transfer study. However, the error associated is considered negligible as the soil water balance model is not very sensitive to root distribution. Retaining the same sampling techniques should ensure that the Y_{ini} values remain the same.

7.2.2.1 *Yield Measurements and Climatological Data*

The pasture yields of several sites on the east coast of the North Island in the Wairarapa were reported by Moir (MAgSc.Thesis, 1994). This included two trial series conducted on sites chosen to represent a variation in climatic conditions, ie., one was located on a high rainfall area at Mauriceville (average rainfall is above 1600mm/yr), and the other on a medium rainfall area at Gladstone (average rainfall is in the range of 950 - 1200mm/yr). Rainfall at the Mauriceville area is generally distributed evenly throughout the year, with no summer-dry period. In contrast, rainfall at the Gladstone area has a tendency to be winter dominant with a slight summer-dry period. The sites were also chosen to represent a range of fertiliser histories and Olsen P levels, as summarised in Table 7.2.

Yield measurements were made using the exclusion cage technique similar to that used at Ballantrae, but herbage cuts were conducted using a domestic hedge trimmer rather than the electric hand shears used at Ballantrae. The hedge trimmer leaves a larger residual value after cutting.

Table 7.2 Some information on the sites located on the east coast of the North Island in the Wairarapa.

Site	Soil Group [Parent Material]	Olsen P (mgP/kg soil)	Fertiliser History
Mauriceville #2	Central YBE [Limestone]	35.2	200kg/ha of SSP over 20 years
Mauriceville #3	Central YBE [Limestone]	28.1	120kg/ha SSP over 10 years
Mauriceville #4	Central YBE [Loess and Siltstone]	10.2	no fertiliser for the last 20 years
Gladstone #10	Central Brown [Redzina, Mudstone]	38.3	200kg/ha of SSP over 15-20years
Gladstone #11	Central YGE/YBE [Intergrade; Loess and Sand/Siltstone]	19.5	no fertiliser for the last 20 years
Gladstone #12	Central YGE/YBE [Integrade; Loess and Sand/Siltstone]	12.6	200kg/ha up to 8 years ago, no fertiliser since

Rainfall data were collected on sites while sunshine hours, and maximum and minimum temperatures were recorded at the closest New Zealand Meteorological Service Station located about 10 - 15km from each site, ie., at Mount Bruce for the Mauriceville sites and at Tauherenikau for the Gladstone sites.

A Y_{ini} of 100kg/ha was used for simulation of pasture yield on three of the sites which have regular SSP fertiliser histories and have Olsen P values above 20mg P/kg soil. On the sites with low or no SSP fertiliser histories, a Y_{ini} of 50kg/ha was used. This was to be consistent with the parameter values used at the HF and LF sites respectively, at Ballantrae.

7.2.2.2 *Results and Discussion*

Figures 7.9 a, b, and c show the simulated pasture growth and the measured harvested yields at the Mauriceville #2, #3, and #4 sites respectively. Figures 7.10 a, b, and c show the simulated pasture growth and measured harvested yields at the Gladstone #10, #11, and #12 sites respectively.

In general, the model appears to under-estimate the measured harvested yields at most sites, except Gladstone #12 where the predicted yields closely agreed with measured yields. The most likely explanation is that the Y_{ini} parameter value at Ballantrae under-estimates the Y_{ini} value at the Wairarapa sites due to the differences in the harvesting techniques used. It is also likely that the $Y_{ceiling}$ and $g_{ceiling}$ values predicted from the Olsen P relationships at Ballantrae (Fig.7.2), under-estimate the values of these parameters for the sites in the Wairarapa.

Firstly, the use of a domestic hedge trimmer in the Wararapa sites and the electric hand shears at Ballantrae may have different effects on the pre-trimming heights. This in turn would create different effects on the equilibrium between root weight and shoot weight (see section 7.2.1.3), which defines the Y_{ini} parameter. While this parameter would have the most effect on the predictions of actual yields at different locations, it is still considered an improvement over the use of total above ground pasture mass because of the lower values associated with it (ie, <200kg/ha compared to >2000 kg/ha for total above ground). After a harvesting event, a great acceleration in growth is always observed. Therefore, it may be possible to develop techniques to conduct detailed research to measure Y_{ini} with more accuracy than total above ground pasture mass.

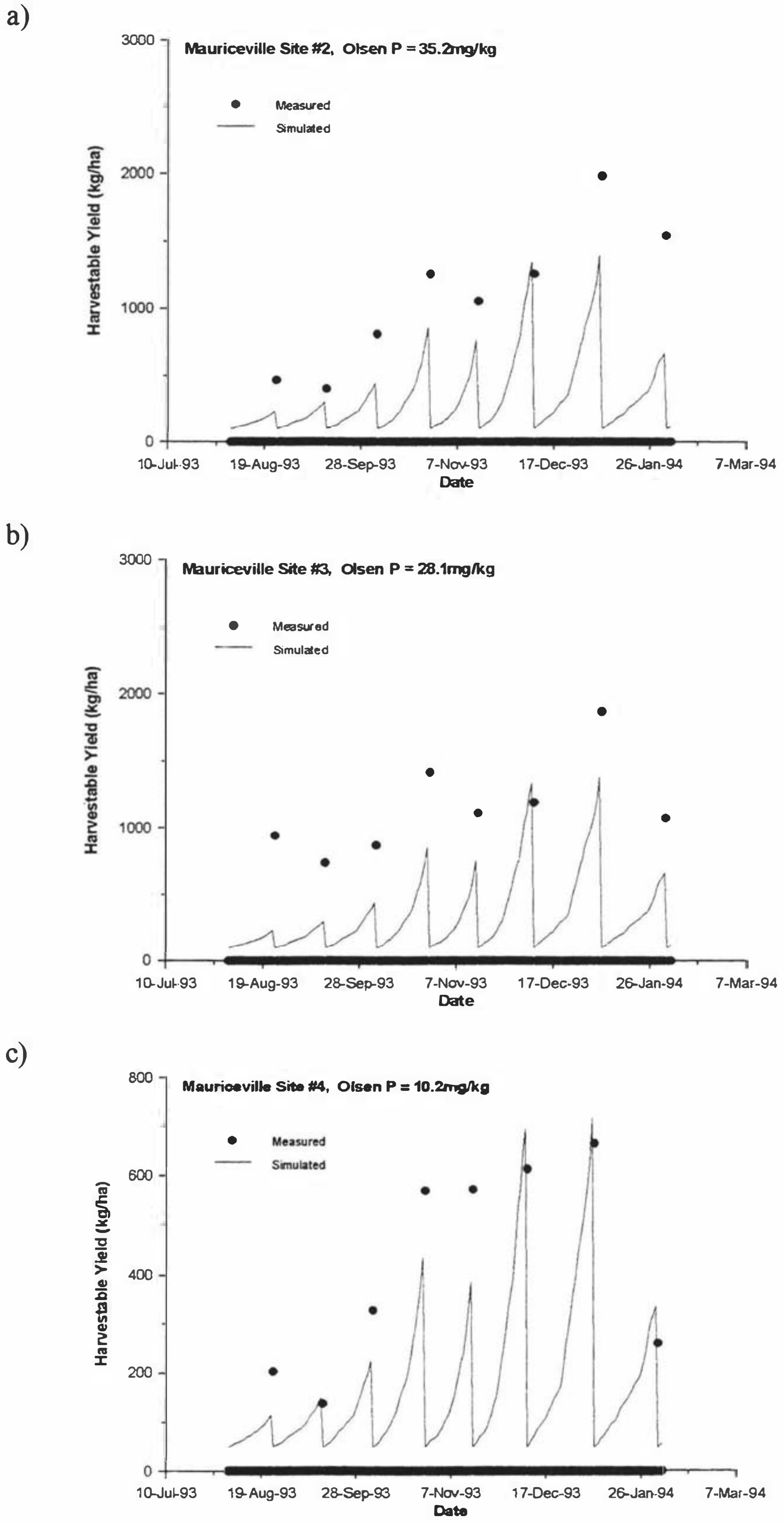


Figure 7.9 Simulated and measured yields at a) Mauriceville #2, b) Mauriceville #3, and c) Mauriceville #4 sites in the Wairarapa.

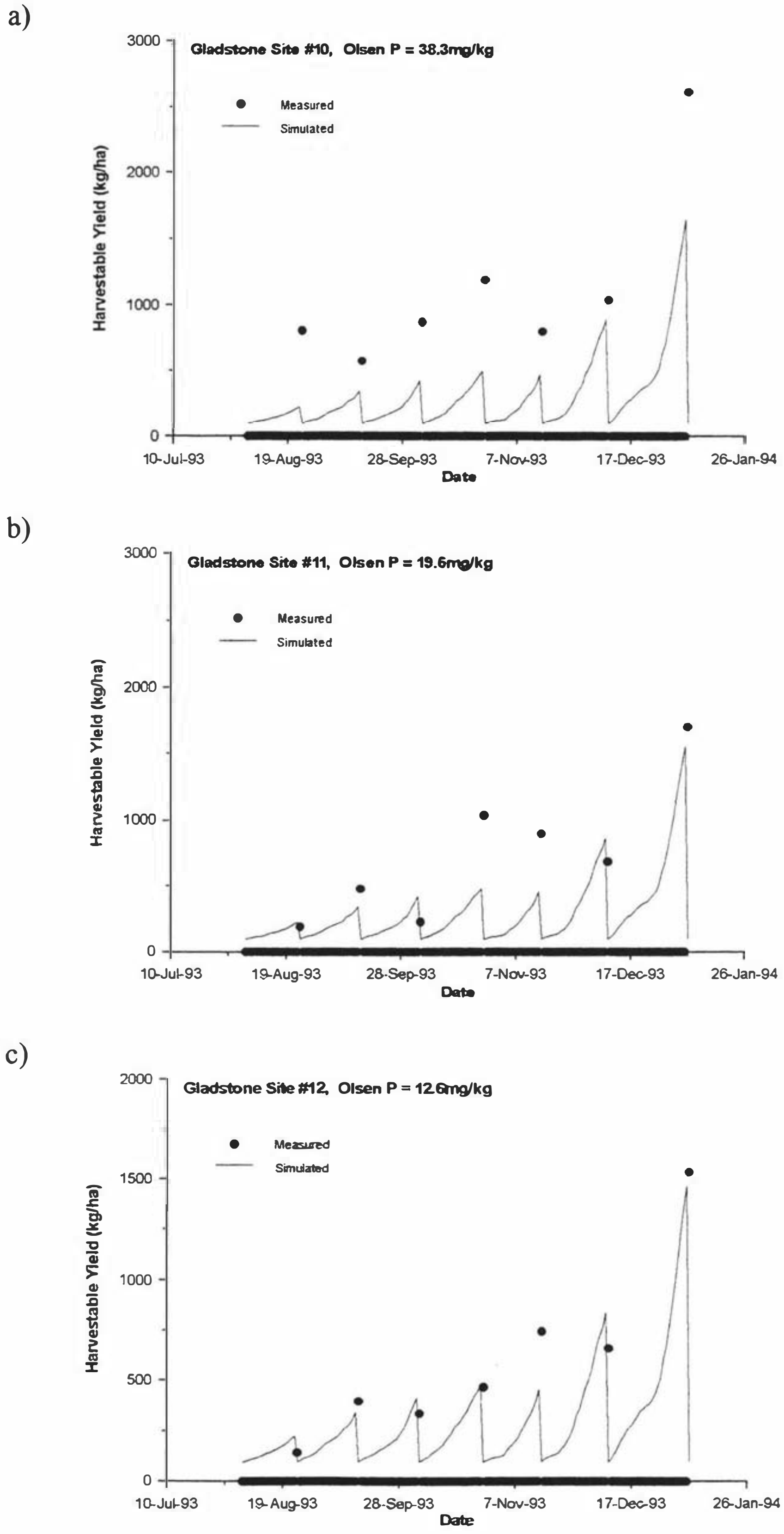


Figure 7.10 Simulated and measured yields at a) Gladstone #10, b) Gladstone #11, and c) Gladstone #12 sites in the Wairarapa.

Secondly, the reliability of using a single range of Olsen P test values as the predictor of the ceiling yields and ceiling growth rates is still questionable. Cornforth and Sinclair (1984) suggested that high P-sorption soils require higher Olsen P test values to obtain the same maximum yields as the low P-sorption soils. It is therefore likely that the Olsen P test cannot be used to predict parameter values used for simulation of pasture growth across all soil types. In addition, other nutrient interactions require consideration. For example, the interaction between +S and +P in promoting legume growth and additional N fixation (reported in Chapter 3) highlights this issue.

While actual yields in the Wairarapa were under-estimated in the simulation when using the parameter values from Ballantrae, the patterns of predicted harvested yields through time did resemble the patterns of measured yields very closely. Again, this highlights the structural strength and the stability of the model, indicating that the parameters it contains are adequate to represent the dependency of pasture growth on climate. However, the variation in the values of the parameters themselves as affected by fertility, still requires improvement.

The next section examines how well the $4\%H_2O_2/KCl_{(16hr)}$ soil S test values can be used to predict $Y_{ceiling}$ of the different sites in the 1990/1992-Ballantrae sites, given the strong correlation with Olsen P values. This provides further opportunity to study the interaction between S and P as it affects pasture productivity. This may also provide an alternative to the Olsen P test to estimate $Y_{ceiling}$ and $g_{ceiling}$ values at sites of different soil types.

7.2.3 Using 4%H_2O_2/KCl$_{(16hr)}$ Extractable S as the Indicator of Soil Fertility to Estimate Initial Parameter Values

In Chapter Four, it was shown that the 4%H_2O_2/KCl$_{(16hr)}$ extractable S test gave a marginally improved explanation of the actual yields on the control plots (section 4.2.3.4), compared to the Olsen P test (section 4.2.3.8), using a Mitsherlich type function. This soil S test was therefore, investigated as a predictor of the ceiling yield values at Ballantrae, using the Michaelis-Menten function (Eqn. 6.12).

7.2.3.1 Y_{max} and $f_{1/2}(S)$

Figure 7.11 shows the relationship when the fertility (F) of the soils in Equation 6.12 is represented by 4%H_2O_2/KCl$_{(16hr)}$ extractable S, and using $Y_{(cut11)}$ as $Y_{ceiling}$, similar to Figure 7.2, using Olsen P. The $f_{1/2}$ value obtained is referred to as $f_{1/2}(S)$, to differentiate it from the $f_{1/2}$ obtained using Olsen P.

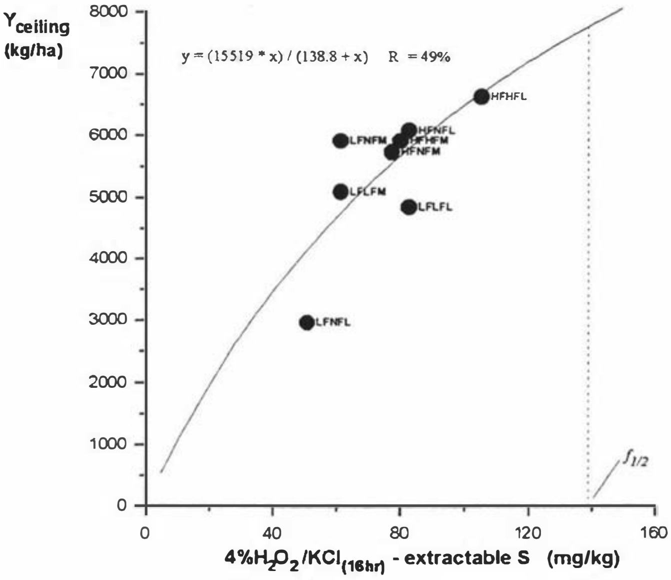


Figure 7.11 Using $Y_{(cut11)}$ data (from 19 November 1991 to 24 January 1992) as $Y_{ceiling}$, regressed against 4%H_2O_2/KCl$_{(16hr)}$ extractable S, using the Michaelis-Menten curve (Eqn. 6.12).

The interesting features of these results (Fig. 7.11) are that, i) the $f_{1/2}(S)$ value of 139mg S/kg soil is well above all the values obtained from all the sites in the 1990/1992-Ballantrae Trials, compared to the model using Olsen P, where the $f_{1/2}$ value of 14mg P/kg soil (Olsen P) was below all the values measured, and ii) the Y_{max} value estimated by this model is much higher than the value estimated using the Olsen P test (Fig. 7.2).

Despite the soil test values for S availability of all the sites being below $f_{1/2}(S)$, there were no S responses to applied S fertiliser. As suggested in Chapter Five, the response to S is dependent on the availability of P and the lack of response is not due to the lack of S supply, but because the amounts supplied by the soils were adequate to utilise soil available P (Lambert *et al.*, 1988,) for legume growth, hence N_2 fixation.

Furthermore, it is important to be reminded that the S cycle has characteristics that are similar to both P and N. The conceptual model proposed by McGill and Cole (1981) suggests that S esters and organic P are stabilised independently of the main organic moiety and can be mineralised through biochemical mineralisation, while the C bonded S appears to be controlled by mechanisms similar to those for N.

The problem is that, losses of S and N from grazed pasture systems are inevitable because the quantities deposited in urine and dung patches are greatly in excess of the capacity of the plants to absorb and the soil to immobilise S in these patches (Sakadevan, 1991). This is caused by grazing stock excreting the bulk of dietary S and N into a very restricted area in comparison with the area from which they were foraged (Ball and Field, 1987; Goh and Nguyen, 1991). Therefore, chronic N deficiencies have been shown to persist in well-managed pastures, even decades after sowing (Ball and Field, 1987). The consequences are that, i) the Y_{max} value estimated by the index of S availability, $4\%H_2O_2/KCl_{(16hr)}$, is merely theoretical and it can never be achieved, and ii) test values below $f_{1/2}(S)$ can be expected, without the systems being S responsive.

Therefore, on one hand there is adequate S to utilise available soil P. On the other hand, the build up of organic S will always be limited while the fixation of carbon into organic matter remains N limited. This is partly due to the inefficient recycling of legume derived N.

Nevertheless, the results shown in Figure 7.11, indicate that the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test appears to give a similar but better spread and explanation of the yield data compared to the same relationship using Olsen P (Fig. 7.2). Therefore, the Y_{max} and $f_{1/2}(S)$ values of 15519kg/ha and 138.8mg/kg are justified as the parameter values that can be used for simulation of pasture growth.

7.2.3.2 g_{max} and Y_{ini}

To estimate g_{max}, the same logic as that applied to the model using Olsen P is also applied (section 7.2.1.2). This assumes that an $f_{1/2}(S)$ of 138.8mg/kg extractable S, will also result from a Michaelis-Menten relationship between $g_{ceiling}$ and $4\%H_2O_2/KCl_{(16hr)}$ extractable S values. Assuming that $g_{ceiling}$ of 44kg/ha/mm or 200kg/ha/day can be observed on the HFHF<u>L</u> site and that the $Y_{ceiling}$ value of the HFHF<u>L</u> is 43% of Y_{max}, then according to Equation 7.1, the $g_{ceiling}$ value of the same site should also be 43% of g_{max}, which corresponds to a g_{max} value of 122kg/ha/mm. The Y_{ini} values are the same as those used for the Olsen P.

A summary of the parameter initial values estimated from the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test are shown in Table 7.3.

Table 7.3 Summary of initial parameter values estimated from the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test.

Parameter	Initial Value
Y_{max}	15519kg/ha
g_{max}	122kg/ha/mm
$f_{1/2}(S)$	138.8mg/kg
Y_{ini}	100kg/ha for the HF sites 50kg/ha for the LF sites

7.2.3.3 *Results and Discussion*

Figures 7.10 and 7.11 show the regressions between simulated and measured harvested yields at the LF and the HF sites respectively, using the initial values that were estimated from the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test (Table 7.3).

The results show that the coefficients of the linear regressions were very similar to those obtained from the simulated harvested yields, using the parameter values estimated from Olsen P (Table 7.1, Figs. 7.5, 7.8). Therefore, while the spread of data was better in the relationship between ceiling yields (Y_{cut11}) and the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test, the predictions of harvested yields were not improved by using the predicted $Y_{ceiling}$ values and the corresponding $g_{ceiling}$ values.

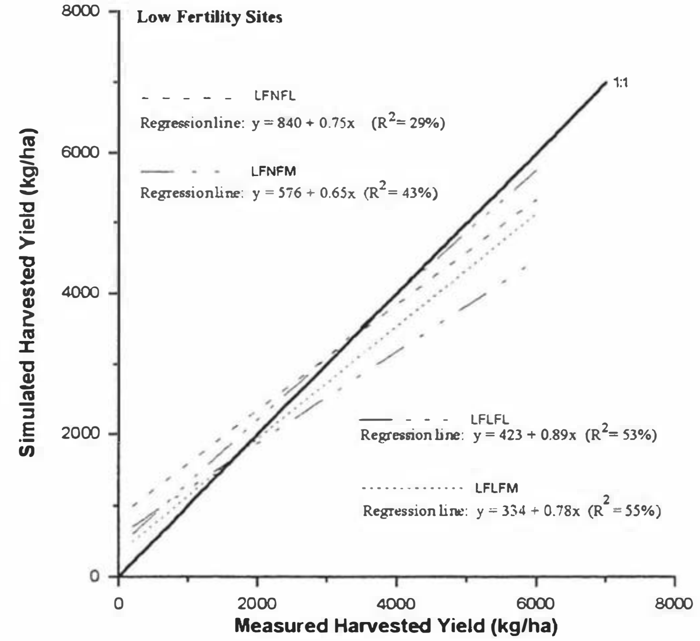


Figure 7.12 Regressions between simulated and measured harvested yields from the sites located on the LF farmlets, using the parameter initial values estimated with the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test.

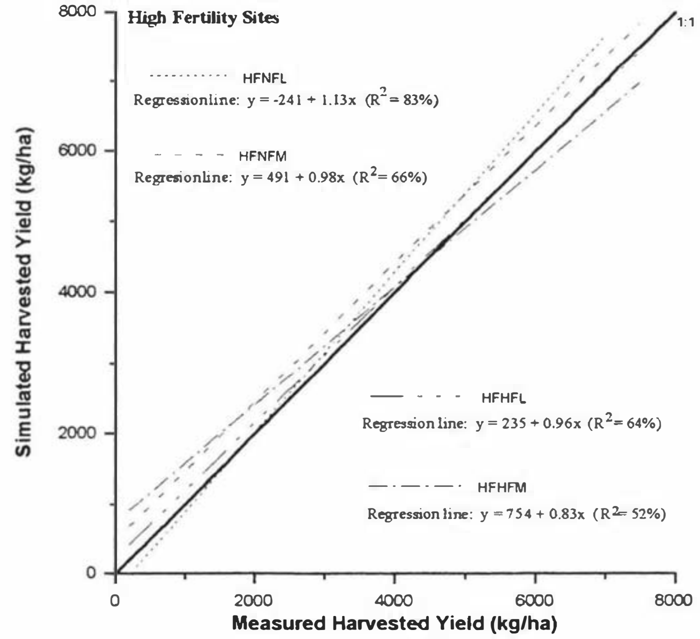


Figure 7.13 Regressions between simulated and measured harvested yields from the sites located on the HF farmlets, using the parameter initial values estimated with the $4\%H_2O_2/KCl_{(16hr)}$ extractable S test.

7.3 GENERAL DISCUSSION AND RECOMMENDATIONS FOR IMPROVEMENT

In the regression models using soil test values(Chapters Four and Five), the coefficients of determination (R^2) are generally low with the scatter of data being caused mostly by the interaction of plant nutrition with water use (Holford *et al.*, 1988). The soil test models presented here, using Olsen P and 4%$H_2O_2/KCl_{(16hr)}$ extractable S already has the variations in climate eliminated. As shown in Figure 6.6, the same value of the $f_{1/2}$. parameter controls the rate of increases in ceiling yields ($Y_{ceiling}$ = kg/ha) and ceiling growth rates ($g_{ceiling}$ = kg/ha/mm) with increasing levels of fertility. Thus, climate is already incorporated into the variations of growth with fertility.

Unfortunately, the ceiling yields and ceiling growth rates were under-estimated with the $Y_{(2w)}$ and $Y_{(4w)}$ data. The uniqueness of this data set was that time was made constant allowing the variations in harvestable pasture mass after each two weekly interval, to be modelled as a function of accumulated ET_a. The 2 weekly intervals however, were not long enough to allow pasture mass standing as cover ($Y_{(2w)}$) to represent the full range obtainable in a sigmoidal growth period, hence, the lower estimates of $Y_{ceiling}$ and $g_{ceiling}$ of each fertility level. Without these variations in harvestable yields standing as cover and accumulated ET_a, the growth rates could not be calculated, but given that the rate of increase in $Y_{ceiling}$ (kg/ha) with increasing fertility is the same as rate of increase in $g_{ceiling}$ (kg/ha/mm) controlled by $f_{1/2}$., estimates of $g_{ceiling}$ could be made when better estimates of $Y_{ceiling}$ were obtained.

The use of $Y_{(cut11)}$ as the ceiling values improved the estimates of the ceiling values at the HF sites, but would have re-introduced some variations in climatic effects on the ceiling values across all sites. The timing in which the asymptote of the growth curves (ceiling) are reached at each site may vary according to the amounts of light that reach the base of tillers as affected by the differences in pasture mass (Matthew, 1992). This may also have had an effect on the Y_{ini} parameter representing the preference of plants to produce shoots after a harvesting event when accumulated ET_a is zero. It therefore appears that the effect of climate could not be removed using one single harvesting event to estimate the ceiling values across a range of fertility levels.

Consequently, while there could be some effects of soil type on the relationships between ceiling values and Olsen P and $4\%H_2O_2/KCl_{(16hr)}$ extractable S, the effects of climate were also not completely removed before the model was transferred away from Ballantrae. As a result, the model was not able to predict accurately the actual yields in the Wairarapa. Nevertheless, the stability and structural strength of the model was reflected by the patterns of the harvested yields predicted through time, closely resembling the patterns that were measured as affected by climatological data. It is concluded that the current model contains the right parameters in its structure, and to maintain its simplicity, better data are required to estimate the current parameter values before further development with new parameters should be made.

It is likely that better estimates of $Y_{ceiling}$ and $g_{ceiling}$ will be gained by conducting field trials with 6 and 8 weekly harvesting regimes on top of the 2 and 4 weekly harvesting regimes, and by maintaining the 2 weekly overlaps so that for every 2 weeks, there is a 2, 4, 6, and 8 weekly harvesting event taking place.

It is obvious that if higher values of Y_{ini} are used, better predictions would be obtained. The exercise however, was not just to find a good fit with measured data, but to find a single framework where soil fertility and climate effects on pasture growth could be incorporated. The advantages of the Y_{ini} parameter over the use of total above ground herbage mass are; i) the errors associated with its estimates are likely to be less because it is a smaller quantity compared to total above ground herbage mass, ii) the acceleration of pasture growth within a day or two of a harvesting event are often very visible, iii) it is based on plant physiological concepts. Designing experiments with these in mind are likely to achieve better estimates than techniques to measure total above ground mass.

Despite the model not being able to incorporate other situations with different soil types together with Ballantrae into a single framework, the added advantages of simplicity while the patterns of harvested yields predicted through time closely resemble measured yields means that this model has a good structure as a basis for future work. For farm management, simpler models are superior because extra complexity will not only make parameterisation difficult, but would require more data.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 INTRODUCTION

The implications of the research findings and models developed in this thesis are summarised and discussed in this chapter. Their applications can be divided into two areas; i) to improve understanding of the interaction between S and P in regulating the N economy of legume based pastures, and ii) to translate soil test results into practical farm management decisions. In addition, the models provide the basis for future work which are suggested in the final section of this chapter.

8.2 SOIL TEST EVALUATIONS USING FIELD TRIALS

The initial objective of the thesis was to produce an improved soil S test which better reflected the involvement of organic S mineralisation in the S nutrition of grazed pastures. Field trials were established with which to calibrate newly developed soil testing procedures. The outcomes of the initial objectives were not realised for two reasons. Firstly, pasture growth at field trials sites at the Ballantrae Research Station chosen to represent pastures where SSP had been withdrawn remained unresponsive to application of S fertiliser alone (+S), unless P was applied (+SP). Thus, soil S tests could not be calibrated against the RY response to S alone. Secondly, although a range of pasture yield increases to applied S with a basal P application existed in the second series of trials (MAF Trials) no relationships between new and conventional soil S tests and the RY responses to applied S could be established. The tentative conclusion from this work is that despite S being considered to be more mobile and more easily lost from grazed pasture than P, P nutrition remains the major constraint on pasture growth. Once the P constraint is alleviated with P fertiliser then S becomes a secondary constraint limiting legume growth, which impacts on the N economy of the sward and total pasture yield.

The data indicate that despite over 20 years of SSP use, a combined S and P fertiliser source such as SSP remains a very appropriate fertiliser for the hill country pastures studied in this thesis. The application of P effectively inducing a greater demand for the S which is co-applied.

Although no one soil S test could predict S responsiveness of pasture growth the amount of S extracted by the $4\%H_2O_2/KCl_{(16hr)}$ test method proved to be a good predictor of the variation in yields under one climate regime caused by long term differences in SSP application rates and variable return of animal excreta. These soil S test values were strongly correlated with the Olsen P test values for each site. Soil tests which can predict yields in long term SSP fertilised paddocks have potential as fertility management tools, as such the $4\%H_2O_2/KCl_{(16hr)}$ test warrants further investigation.

The failure of the yield responses to S (above basal P) in the MAF Trials to correlate with soil S test values is suggested to occur for a number of reasons. One reason is that RY is not an effective device for controlling the large differences in the yield caused by the variation in climate at each site. A further reason is that basal P application would stimulate different increases in pasture yield depending upon the current soil P test status and P sorption characteristics at each site. Normalising these interactions of P with site and with S would require the following sets of treatments; unfertilised control, +P, +S, +SP.

It was concluded that the hidden interactions of P with site and with S are largely controlled by climate, contributing to the large unexplained variation observed in RY calculated in this thesis. It was considered that a better device than RY was required to normalise yields between trial sites so that they can be used in a common framework to calibrate soil tests. Accordingly, it was decided that the remainder of this thesis should be devoted to providing a mechanism by which the climatic effects could be incorporated into the relationships between pasture yield and soil fertility evaluation.

8.3 INCORPORATING THE EFECT OF CLIMATE INTO THE RELATIONSHIPS BETWEEN PASTURE YIELDS AND SOIL FERTILITY

8.3.1 Model Development

The first objective was to find a quantitative measure of climate. It was assumed that climate could be adequately represented by rainfall, average temperature, and sunshine hours. These climatological data were integrated into a soil water balance model to predict actual evapotranspiration (ET_a) which represents climate quantitatively as the amount of water used for pasture growth. At the Ballantrae farmlets, predicted soil water contents closely resembled values that were measured in 2 weekly intervals throughout 1993. The accumulated ET_a value over each 2 weekly interval was therefore considered as an adequate representation of the amount of water that was used by pasture for growth over the same period.

Pasture growth over 2 weekly ($Y_{(2w)}$) and 4 weekly ($Y_{(4w)}$) harvesting regimes were collected over the same year which provided a data set of variable pasture masses with associated accumulated amounts of ET_a over the same intervals. Pasture growth as affected by the amount of harvestable pasture mass standing as cover ($Y_{(2w)}$) and ET_a

was modelled using a quadratic function in which net growth is the balance between new growth and damping by self-shading. It was shown that the quadratic function could be manipulated to obtain ceiling yields ($Y_{ceiling}$) and ceiling growth rates ($g_{ceiling}$) at each site.

The dependency of $Y_{ceiling}$ and $g_{ceiling}$ at each site of different fertility could be explained from the Olsen P level at each site using Michaelis-Menten kinetics. It was found that both $Y_{ceiling}$ and $g_{ceiling}$ values increased at the same rate with increasing fertility towards maximum yield (Y_{max}) and maximum growth rate (g_{max}) values unconstrained by fertility. The rate of increase were controlled by the parameter $f_{1/2}$ (the Michaelis-Menten constant), which is the fertility level at which 50% of Y_{max} and g_{max} are obtained. The $f_{1/2}$ parameter is believed to provide a simpler and more descriptive measure of a site's relative fertility level than the arbitrary rate constant in the Mistcherlich type models commonly used to model pasture growth dependency on soil fertility.

8.3.2 Model Evaluations

The rates of increase in $Y_{ceiling}$ and $g_{ceiling}$ values being controlled by the same $f_{1/2}$ at Ballantrae, illustrated the structural strength of this modelling approach. However, the $Y_{ceiling}$ and $g_{ceiling}$ values were generally under-estimated because using the $Y_{(2w)}$ data as pasture mass standing as cover, did not represent the full range of pasture mass represented in pasture growth sigmoid curves. A better estimate of Y_{max} was obtained when a single long harvesting event (9weeks) in summer1991-1992 was used as ceiling yields ($Y_{cut11} \equiv Y_{ceiling}$). As variations in $Y_{ceiling}$ and $g_{ceiling}$ with fertility were both governed by the same $f_{1/2}$ value, it was therefore possible to estimate g_{max} iteratively.

These estimates of the parameters were used as initial values to simulate pasture growth at different sites at Ballantrae from autumn 1990 to autumn 1992. Both the Olsen P and $4\%H_2O_2/KCl_{(16hr)}$ extractable S tests were used as indices of soil fertility. It was shown that the model predicted the yields at the HF sites with adequate accuracy, but generally under-estimated the yields at the LF sites.

The same parameter values were used to simulate pasture growth at other sites in the lower North Island on different soil types and a wider range of climatic conditions. The predicted seasonal variations reflected by the predicted harvested yields through time were modelled well by the variations in computed ET_a. However, the actual size of the predicted yields varied more extensively from the measured yields. It was concluded that the predicted $Y_{ceiling}$ and $g_{ceiling}$ values from the indices of soil fertility using a single harvesting event (Y_{cut11}), do not represent the real variations of these parameters with fertility.

8.4 RECOMMENDATIONS FOR FUTURE WORK

The results from the model reported in the second part of this thesis suggest that the model developed is structurally robust. For the purposes of farm management, simpler models are preferred. It is suggested that for the sake of simplicity, efforts to improve the existing parameters would be more fruitful in the short term, than introducing new parameters.

Improvements of estimates of the current parameters can be achieved by adding a 6 and 8 weekly harvesting interval regime to the data set to get better estimates of Y_{max} and g_{max}. The variations in $Y_{ceiling}$ and $g_{ceiling}$ with fertility may then be improved using a more reliable estimate of $f_{1/2}$. In addition, Y_{ini}, is an important parameter representing the vigorous after harvest growth when accumulated ET_a is close to zero. Better estimates of this parameter are required for the model to be made more precise. Measurements of yield when accumulated ET_a are below 10mm would be required.

As suggested in section 8.2, further examinations of the use of $x\%H_2O_2/KCl_{(16hr)}$ is highly recommended as the direction for improving indices of soil fertility, in particular the development of their potential to be used as bi-nutrient soil tests. These examinations should be conducted within the mechanistic framework of the simulation model presented in the latter chapters of this thesis, rather than using RY device.

Further developments should make use of the robust structure of the model presented. Its in built soil water balance should allow nutrient cycling and loss components to be incorporated easier. This is important as such models should consider the wider impact of raising soil fertility on drainage.

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