Abstract of a dissertation submitted in partial fulfilment of the requirements for the Degree of Bachelor of Agricultural Science with Honours.

Effects of lime, phosphorus and sulphur on the establishment of Hairy Canary and Tagasaste on an acid high country soil.

By Laura Jean Keenan

Abstract

Legumes play a critical role in New Zealand high country farming systems as the sole provider of nitrogen (N) to the pasture sward through biological nitrogen fixation. N also increases the quantity and quality of pastures increasing animal performance, and overall farm productivity and profitability. However, high country soils are commonly acidic, resulting in high concentrations of exchangeable soil aluminium (Al), low soil fertility and moisture stress. Traditional legumes commonly grown in New Zealand high country fail to successfully establish and persist. Alternative legume species that are adapted to acidic soils with low levels of phosphorus (P) are required. Literature on alternative legumes and their soil fertility requirements at establishment is scarce or non-existent.

Two woody perennial legume species, tagasaste *(Chamaecytisus palmensis)* and Hairy Canary (*Dorycnium hirsutum)* were investigated in a pot trial for 32 weeks at Lincoln University. Plants were established and grown in an acidic high country soil collected from Armidale station, Central Otago. The initial establishment period was under controlled external conditions, before pots were moved into the glasshouse in mid-April. The trial was a fully replicated complete factorial design of two species and 22 treatments. Lime (100% $CaCO_3$) was applied at four rates (0, 2, 4 and 8 t lime/ha) and P at four rates (0, 50, 150 and 500 P/kg). Sulphur (S) was applied to most treatments at 120 kg S/ha (Gypsum) with a complete 'optimum' treatment and a zero S control treatment also included. Plants were harvested five times during the experiment, twice in autumn and three times in winter. Shoot and root yields and lengths were measured and root nodule scores determined. Winter shoot herbage was analysed for macro and micronutrient concentrations. Soils were analysed for pH, P and S contents at the completion of the experiment.

Hairy canary was the highest yielding species (4.07 g DM/pot at a soil pH of 5.4), however, for the first two harvests tagasaste grew faster than hairy canary. Total shoot yield for both species ranged from 2.32 to 4.32 g DM/pot. Lime substantially increased the yields of both species to a maximum point, beyond which yields declined with further lime additions. Lime addition significantly increased ($P < 0.05$) the mean root yield of both legume species. At the most acidic soil pH (pH 4.9) hairy canary was the most productive legume species with a maximum root DM yield of 0.78 g DM/pot, producing 105% greater root mass than tagasaste. The tolerance of these alternative legumes to acidic soils is evident as the greatest root dry matter response occurred at a pH of 5.0 - 5.5 (lime rate 2 – 4 t ha^{-1}).

Soil pH was the key driver of yield where increased soil pH reduced soil exchangeable Al levels which in turn increased shoot molybdenum (Mo) and P concentration. Tagasaste was the most responsive legume to phosphorus inputs and experienced the greatest shoot and root growth at the lowest P levels (0 - 50 mg P kg^{-1}). At high lime rates shoot concentrations of Boron (B) and P declined, reducing legume yields. The results show the potential for tagasaste and hairy canary to provide a nitrogen source and high quality feed in acidic conditions typical of the high country. The lack of research in this area indicates the need for these results to be confirmed by field experiments.

Applied phosphorus did not increase the DM yield of hairy canary or tagasaste. The initial soil Olsen P was at a 'medium' level (17 µg mL^{-1}), hence plant yield response to phosphorus was not significant. Sulphur application caused a significant yield response for both species. Winter and autumn nodulation of tagasaste was significantly increased by lime rate and peaked a pH range of 5.0 – 6.5, which may be directly related to nitrogen fixing ability across a range of soil pH values.

The optimum soil pH and Olsen P levels in the soil have been identified for the successful establishment of hairy canary and tagasaste. Their potential growth on acidic high country soils represents valuable and exciting new information. There is a need to confirm the results of this experiment in the field environment under natural climate and grazing conditions, to determine if similar establishment and yield responses would occur in New Zealand high country.

Keywords:
Chamaecytisus palmensis, Dorycnium hirsutum, high country, establishment, DM yield, soil pH, exchangeable soil aluminium, nitrogen, phosphorus, sulphur.

Acknowledgements

The success of this year would not have been possible without the help and support from many people within and outside of Lincoln University. Therefore I wish to acknowledge and express my appreciation to the following people.

Dr Jim Moir for providing constant guidance, personal attention, suggestion and endless encouragement throughout this year. Your vision and knowledge about soils is astounding and I am thankful for the countless hours of time you have given me.

Mr Lucas for the ongoing support and recommendation throughout this experiment. Your knowledge of plant science and literature is incomparable.

Simon and Alan Patterson, owners and operators of Armidale station, for allowing us to collect soil from their property used in this experiment.

Lynne Clucas for doing the ICP analysis as these were a critical part of my experiment.

Brent Richards, the nursery and field service staff for all of your technical assistance through the duration of this experiment. Your contribution to the practical aspects of this experiment was appreciated.

To all my friends at Lincoln whom I have got to enjoy this experience with. Your ongoing support, motivation and encouragement makes things all the more enjoyable.

A special thank you to my parents, Gavin and Janice Keenan, my partner Sam Sidey and my siblings who has given me so much encouragement and help during this entire process. I would not have succeeded without your constant backing.

Table of Contents

List of Tables

List of Figures

List of Plates

Chapter 1
Introduction

The high country of New Zealand have soils that are subjected to harsh climatic conditions and are strongly influenced by altitude and topography. Many areas experience temperature extremes and conditions such as summer droughts, winter snow, variable rainfall and acidic, low fertility soils (Scott *et al.* 1995), which present substantial challenges in establishing legume species that will grow and persist. Many high and hill country soils are low in plant available nitrogen, phosphorus, sulphur and molybdenum (Kemp *et al.* 1999). In many high country areas it is uneconomic to apply large amounts of lime aerially to increase the pH of the soil and therefore they fail to produce high yields and the legume content is severely reduced (Craighead 2005).

Legumes are essential to low fertility soil systems as the sole provider and source of nitrogen for sward growth, through the process of atmospheric biological nitrogen fixation, particularly as N is the key limiting factor for sward growth in these systems (Maxwell *et al.* 2012). In addition, legumes represent high quality feed and are therefore important for high live weight gains in grazing animals. Past research in New Zealand has focused on commonly sown legume species such as white clover. Although a major component of some pastures, this species is not suitable to low soil fertility and drought prone conditions. Therefore, there is a need for alternative legume species which are better adapted to acid soils with low soil phosphorus and can survive the harsh climatic conditions.

There is currently a lack of suitable legumes able to establish and persist in the high country due to the low soil pH (pH < 5.6) and high levels of toxic exchangeable aluminium (Moir & Moot 2010). Nitrogen (N) is the key nutrient limiting plant growth in this environment, and the only supply of N is through biological fixation by legumes, as it is uneconomic to apply synthetic N fertilisers. By improving the soil fertility and providing adequate conditions for N_2 fixation, the total N available in the soil pool will increase, translating directly to improvements in farm productivity and profitability.

Tagasaste, also known as tree lucerne, is a drought tolerant, woody, perennial legume which is potentially well adapted to soils with a low pH down to a pH below 5.0 and can grow well in soils with low levels of available phosphorus, nitrogen and molybdenum (Jordan 2011; Townsend & Radcliffe 1990). Hairy Canary is a perennial plant with the ability to provide stock with forage under cold, dry, low soil fertility conditions (Willis *et al.* 1989). To date, no literature has covered the soil fertility requirements for successful hairy canary establishment.

This experiment consisted of a factorial design pot trial, with the establishment phase carried out under controlled external and glasshouse conditions at Lincoln University. The experiment allowed for accurate control and manipulation of climate and soil fertility conditions (soil pH, P and S fertility). The aim was to quantify the effects of soil pH and fertility on key plant establishment variables of Tagasaste and Hairy canary. These include shoot and root yield, shoot and root length, shoot nutrient concentrations and nodulation response to soil chemical variables at different stages of establishment.

The objective of this study is to determine the soil fertility requirements of these two species during establishment and to evaluate the viability of tagasaste and hairy canary to establish and grow in an acid high country soil.

Chapter 2
Literature Review

2.1 Introduction

Pasture legumes are critical to grazed pasture farming systems for two key reasons. The first is related to soil fertility because legumes are the primary source of nitrogen via biological nitrogen (N) fixation, while the other relates to their role of the supplier of high quality animal feed (Kemp *et al.* 1999), improving farm profitability. Soil pH also plays a critical role in the growth of plants and interactions with other nutrients, potentially causing deficiencies or toxicities at a high or low pH (McClaren & Cameron 1996). Phosphorus (P) is second only to N as the key macronutrient driving the productivity of legume based grazed pasture systems (Moir *et al.* 1997).

Traditional pasture legumes often perform poorly in dry summer and cool winter high country environments. Investigation into alternative dryland legumes adapted to this environment are required. This literature review will focus on two potential species for hill country production: *Chamaecytisus palmensis* (tagasaste) and *Dorycnium hirsutum* (hairy canary). Current literature on climate and soil fertility conditions required for the success of these species will be covered in this review.

2.2 Physical conditions of the high country

2.2.1 Climate

The high country is characterized by having the lowest mean temperatures and greatest extremes in mean monthly temperature than any other area in New Zealand (Scott *et al.* 1995). Allan (1985) explained how the low winter temperatures of the South Island high country causes the growth of the majority of pasture species to cease from mid-April to mid-October. Moisture in the high country is a fundamental factor controlling pasture production and is unable to be modified from the natural distribution pattern, as irrigation and drainage are not viable options in this environment. The amount of soil moisture available for plant growth depends upon altitude, slope and aspect and the moisture retention characteristics of the soil. The high climatic variability across the high country requires adaptive systems to manage the risk of feed shortage and animal safety.

Scott *et al.* (1995) illustrated the effect of climate on soil type (Figure 2.1) and how the interaction between soil moisture and temperature result in a characteristic pattern of soil types which severely constrain the farming options in high country. As temperature increases the weathering of soil minerals releasing nutrients, increases. Combined with high rainfall, the rate of nutrient loss via leaching through the soil profile is dramatically increased. The distribution of soil types in the high country is directly related to these variations in temperature and moisture (Scott *et al.* 1995).

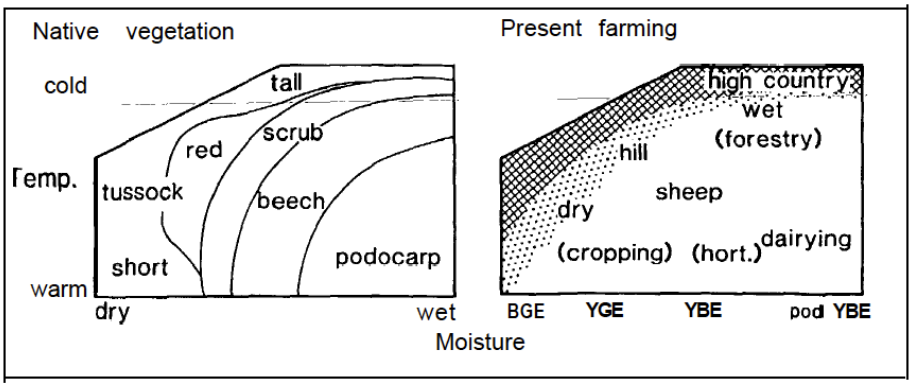


Figure 2.1 Distribution of original vegetation and present farming practices in New Zealand in relation to the environment gradients of temperature and moisture. Sourced from Scott *et al.* (1995).

2.2.2 Soils

The high country of New Zealand is primarily made up of yellow grey and yellow brown earths and their intergrades, which are generally acidic with a pH of 5.5 or less, while heavily leached areas are often below pH 5.0 (McClaren & Cameron 1996). These factors combined with the low available phosphorus and sulphur has limited the persistence of legumes (Moir & Moot 2010). In many high country areas is uneconomic to apply large amounts of lime aerially to increase the pH of the soil and therefore they fail to produce high yields and the legume content is reduced (Craighead 2005).

The distribution of soils in the high country is related to variations in temperature and moisture. Brown grey earths are weakly weathered and leached, occurring across areas of high country at lower altitude, whereas yellow-brown and yellow-grey earths are progressively more leached as they occur on slopes with increased altitude and are more susceptible to nutrient and water run off (Figure 2.2). The higher altitude results in decreased temperatures, slowing down the weathering process resulting in soils with sever nutrient deficiencies. The environmental gradient continues with podzolised yellow-brown earths present in alpine soils having the lowest potential for pastoral agriculture as they suffer from the greatest nutrient deficiencies as a consequence of the high rainfall and strong leaching. The persistence of many legume species in this environment is limited; thus alternative legumes better adapted to these conditions are sought.

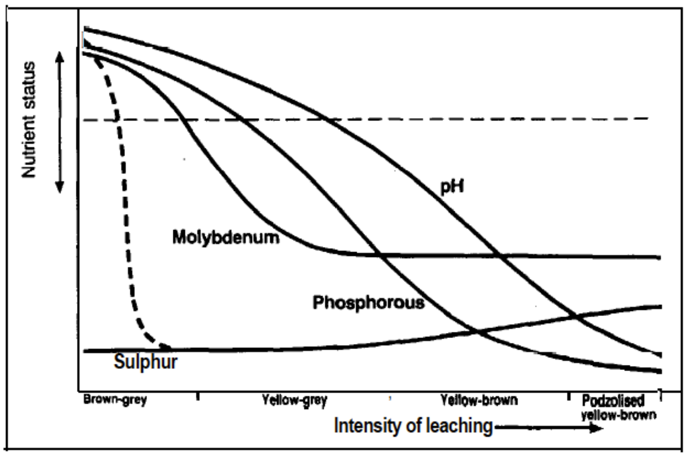


Figure 2.2 Soils, nutrient status and fertiliser requirements for a series of high country soils in relation to rainfall and leaching. Sourced from Scott *et al.* (1995).

2.3 Soil pH

Most high country soils in New Zealand have a pH below 5.5 as they are located on high terraces and are exposed to periodic weathering. These factors combined with the low available phosphorus and sulphur has limited the establishment and persistence of legumes (Moir & Moot 2010). Soil pH decreases from the weathering of parent materials, leaching of bases, the formation of soluble acids, the release of hydrogen ions by plant roots, aluminium hydrolysis and fertiliser application which accelerate the cycling of nitrogen, sulphur, carbon and phosphorous, all releasing H^+ ions into the soil (Bolan & Hedley 2003). Soil pH is a direct measure of the concentration of hydrogen ions present in the soil solution and is calculated using the following equation:

$$pH = -\log_{10}[H^+]$$

2.3.1 The effect of soil pH on nutrient availability

The pH of soil has a significant effect on the availability of nutrients (Figure 2.3). Acidic soils can make plants deficient in nutrients such as phosphorus (P), molybdenum (Mo), magnesium (Mg) and calcium (Ca) or can contain toxic amounts of aluminium (Al). Given that most of the high country in New Zealand has a pH below 5.5 sever nutrient deficiencies are likely to be present.

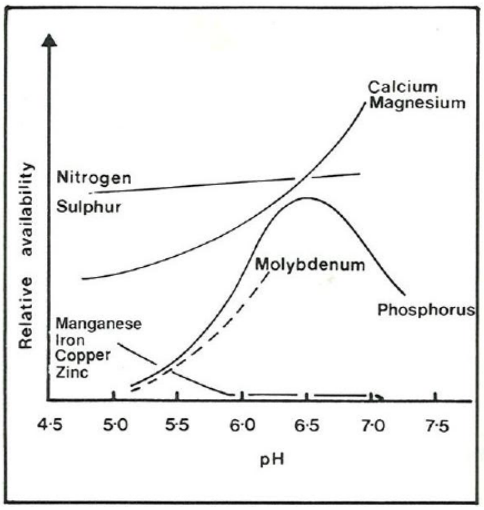


Figure 2.3 The effect of soil pH on the availability of nutirients. Sourced from McClaren and Cameron (1996).

P is also of particular interest as it increases in availability up to a pH of 6.5 and then declines rapidly. P availability is heavily affected by pH due to chemical changes in the soil, under alkaline and acidic conditions (Figure 2.4). At low pH P adsorption occurs with Al and Fe minerals and P becomes unavailable. At high pH, Ca and Mg phosphates form, fixing the P into forms that are unavailable to plants (Figure 4) (Sanyal & Datta 1991). Phosphate fixation is at a minimum between a pH of 6-7, therefore between this range the maximum amount of P will be available for plant uptake (Figure 2.4).

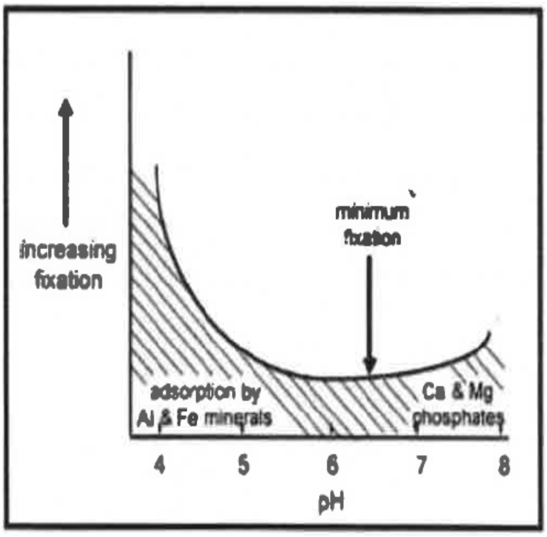


Figure 2.4 The effect of pH on phosphate fixation by soils. Sourced from McClaren and Cameron (1996).

2.3.2 Effect of pH on soil and plants

The availability of many essential nutrients in the soil solution is determined by pH, and therefore pH effects plant growth. The main limiting nutrients under acidic conditions are Mo and P, while Al and Mn can become toxic (Wheeler & O'Connor 1998). An increase in soil pH through the addition of lime, can result in an increase in the bioavailable N, P and Mo in the soil and thus a positive yield response. Lime inputs also increase the soil moisture content, yet decrease the level of available aluminium and manganese (Craighead 2005).

The ability of legumes to fix atmospheric nitrogen in a symbiotic relationship with *rhizobium* bacteria is effected by soil pH by way of influence on the activity of rhizobia to nodulate successfully, decreasing the nitrogen available for plant growth. Different rhizobia are associated with different legume species and may have varying tolerance levels to acidic soil conditions limiting their ability to form functional root nodules at low pH's (Correa *et al.* 2001). This is critical in the high country, where the main input of nitrogen into the system is through N fixing legumes.

2.3.3 Aluminium toxicity

Aluminium is not essential for plant growth, but can effect plant growth and development. At a pH below 5.8, the level of soluble Al increases causing Al^{3+} to displace other cations from exchange sites and subsequently these cations are leached from the soil, leading to aluminium toxicity (Moir & Moot 2010). Al toxicity rarely occurs in soils with a pH greater than 5.8 and the problem usually occurs in the sub soil, impairing root development and elongation (Maxwell *et al.* 2012). The inhibition of root cell elongation and division results in reduced nutrient and water uptake and thus increased risk of drought susceptibility.

2.3.5 Liming

Lime is an important management tool for high country farmers as the application increases soil pH, making essential nutrients available for plant uptake. Generally, the response to lime increases as the soil pH decreases. Maxwell *et al.* (2012) indicated that most clover species had a positive response to increasing soil pH levels above 5.0, with maximum dry matter yields occurring at a pH of 5.2 – 5.7.

Lime is a relatively insoluble material and the pH increasing ions (OH^-, HCO_3^- and CO_3^-) take many years to travel through the soil profile, thus it is recommended to incorporate lime into the soil if cultivating. Liming increases the pH of the soil and lowers the level of exchangeable Al. This effect is most obvious in the surface (0-75mm) soil horizon (Moir & Moot 2010). Edmeades *et al.* (1983) illustrated pasture growth responses to liming across 140 lime application trials, at a soil pH of 5.0 and 5.5 lime increased pasture production by 5 and 10% respectively. Pasture responds to lime because of the reduction in aluminium toxicity. The increase in plant available phosphorus, boron and molybdenum is also critical to the pasture response and increasing the legume component on a pasture sward. Jordan (2011) illustrated that under optimum lime conditions tagasaste yield increased by 34% due to macronutrients being non limiting.

2.4 Phosphorous

Phosphorus is a critical macro nutrient for productive developed pastures, particularly for legume growth and persistence in the sward. In many high and hill country systems, legumes are the only source of nitrogen input via fixation to alleviate the chronic N deficiency in this highly weathered environment (Lambert *et al.* 1988). P is considered deficient in the plant at levels less than 0.30% of DM (Morton & Roberts 1999). P is a constituent of adenosine triphosphate (ATP) and adenosine diphosphate (ADP), the main energy sources for the majority of cellular functions. P is also a component of nucleic acids and thus DNA, as well as phospholipids which make up cell membranes and several essential co-enzymes which are required for the proteins biological activity (Raven *et al.* 1992).

2.4.1 The phosphorus cycle

The P cycle (Figure 5) illustrates how P is gained, lost and transformed within the soil / plant / animal / atmosphere system. A significant amount of the P ingested by grazing animals is returned to the system in the form of dung and decomposing plant material. Approximately 20 – 35% of the P taken from the soil is lost from high country systems as meat and wool, while significant amounts of P removed by plants is cycled back into the system through animals and their subsequent excreta (Figure 2.5). Also in hill country environments, around 60% of the nutrients can be deposited onto stock camps which only make up 13 – 30% of the total land area (Kemp *et al.* 1999). Virtually no P is found in the urine of grazing animals.

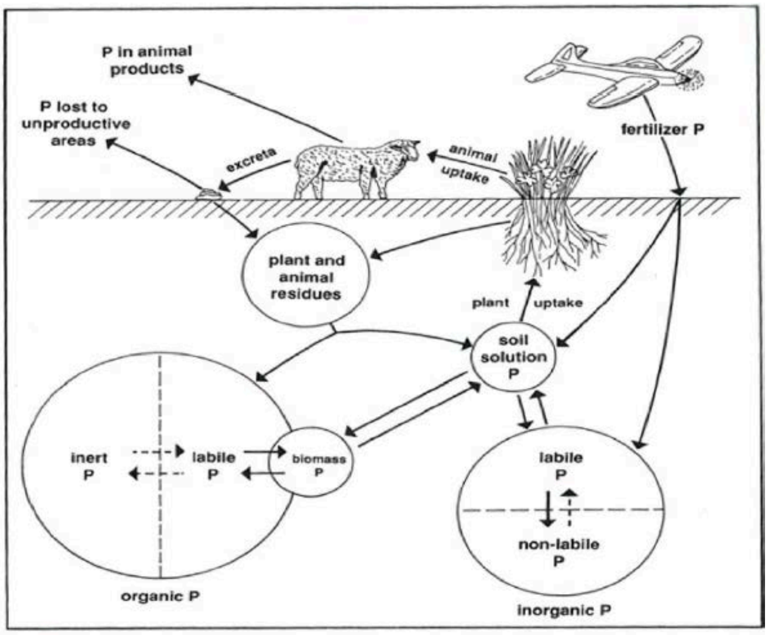


Figure 2.5 The phosphorus cycle in grazed pasture systems. Sourced from McClaren and Cameron (1996).

2.4.2 Phosphorus acquisition and availability

Plant roots obtain P from the soil solution in the form of monovalent phosphate anions ($H_2PO_4^-$) and less rapidly as the divalent P anion (HPO_4^{2-}) through the process of mass flow and diffusion (Syers *et al.* 2008). Diffusion is the main mechanism of P uptake due to the concentration gradient created between the root P and soil P (Mengel & Kirkby 2001). The availability of the two anions is dependent on pH and as high country soils are typically acidic, the majority of phosphate is likely to be in the form of $H_2PO_4^-$ (Figure 2.6).

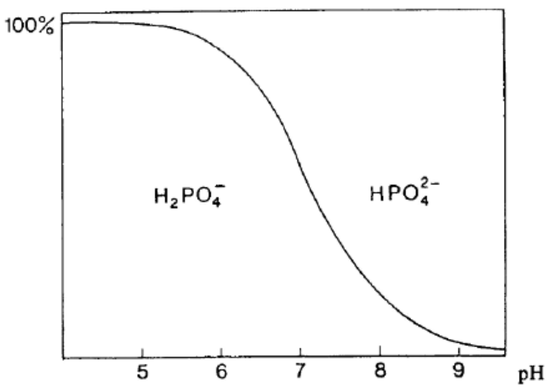


Figure 2.6 Availability of $H_2PO_4^-$ and HPO_4^{2-} in relation to soil pH. Sourced from Mengel and Kirkby (2001).

The bioavailability of P to plants is effected different forms of P in the soils such as liable and non-liable P fractions. Insoluble or fixed forms of P make up 90% of P in the soil and include non-labile forms of P such as primary phosphate minerals such as calcium, iron an aluminium phosphates (McClaren & Cameron 1996). However P in the soil solution is normally fully available for plant uptake. Another source of available P is the liable soil P which is bound to the soil surface or in phosphate precipitations which are in equilibrium with the soil solution (Mengel & Kirkby 2001), and thus available for plant uptake (Figure 2.7).

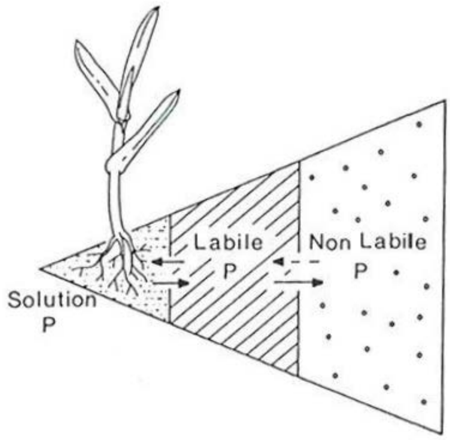


Figure 2.7 Interactions between P in the soil and soil solution in relation to plant availability. Sourced from Mengel and Kirkby (2001)

The P content of soil ranges from 0.02 to 0.15% depending on the degree of weathering of the different parent materials and leaching that has occurred (McClaren & Cameron 1996). Traditionally, single super phosphate (SSP) has been applied to New Zealand soils and it contains between 8.5 and 10% P and 10 – 12% sulphur (S). In high country pastures, phosphate fertiliser applications are used to increase the legume, and subsequently the perennial ryegrass (*Lolium perenne* L.) content of the sward. Thus, a plants ability to access and compete for resources will influence herbage accumulation rate, and the content of that species within the pasture sward. Lambert *et al.* (1986) found that P fertiliser applications increased the legume content initially which led to a higher amount of N being symbiotically fixed. This nitrogen was then cycled back into soil increasing the total N pool, and thus increasing the competitiveness of associated grasses, suppressing the legume component of the sward.

2.4.3 Pasture response to added P

Historic SSP inputs are generally associated with higher soil Olsen P status and increased dry matter production (Moir *et al.* 2000). The general relationship between soil Olsen P and grass yield for a particular soil is illustrated in figure 2.8. Above and Olsen P value of 20 ug ml^{-1} there is no extra dry matter is produced indicating that pastures exhibited luxury P uptake occurs and other factors must be response for limiting pasture yield. This example shows that pastures are strongly responsive to P additions (are P deficient) below an Olsen P of 20 ug ml^{-1}.

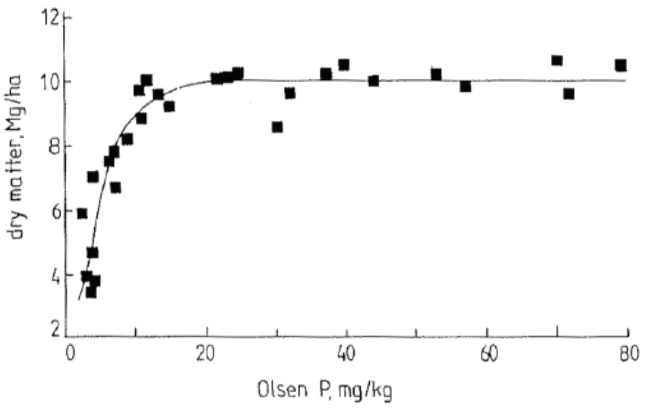


Figure 2.8 The effect of Olsen P on pasture yield. Sourced from Mengel and Kirkby (2001).

Differences between plants in their response to P may be partly due to differences in the efficiency in which they use P to photosynthesize. Barrow (1975) illustrated that ryegrass requires less phosphate than clover for near-maximum yield of young plants. Ryegrass has a larger capacity to absorb phosphate as ryegrass has a lower P concentration at its root surface, thus increasing the absorption rate. Thinner roots and longer root hairs also increase the explorative potential of roots within the soil, increasing the proportion of phosphate within range of diffusion to the ryegrass root (Barrow 1975).

2.5 Sulphur

Soil sulphur comes from soil parent material and fertilisers, with small but agronomically significant inputs from the atmosphere. As the soil parent material weathers sulphate ions are released, which are extremely mobile and unless they are taken up by the plant they are lost via leaching (McClaren & Cameron 1996). The gains, losses and transformations of sulphur within the soil / plant / animal system determine the amount of S available for plant use and include being taken up by plants and then ingested by grazing animals, before it is returned to the soil by animal excreta or plant residues. In agricultural systems the main addition of sulphur has been through historic and current applications of superphosphate, mainly for phosphate deficient soils, but the fertiliser also contains 10 – 12% S. As the concentration of sulphate increases up to 4 mg S/kg soil the economic yield is achieved, at 85% of relative yield (Figure 8). The exponential increase up to 5 mg S/kg soil illustrates how attainable it is to achieve near maximum yields with low fertiliser applications.

In a study by Voon (1986) sulphur had little effect on the yield of tagasaste except at the application rate of 160 g P/pot where the yield of plants not treated was significantly lower than this treatment (19 g DM/pot v 17g DM/pot for with S and without S, respectively). However, the most important function of S is to stimulate nitrogen fixation by legumes. These associations where reiterated in the same study, where the main S association was with nodulation, with visual root nodule score increasing with the positive addition of S fertiliser. This same function may occur in hairy canary, however, the literature does not provide any supporting information.

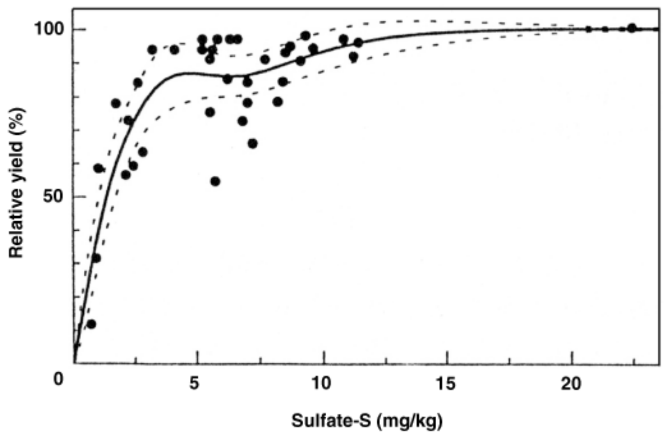


Figure 2.9 the relationship between relative yield and the concentration of sulphate for a range of New Zealand soils. Sourced from Maxwell *et al.* (2012).

2.6 Trace elements

2.6.1 Molybdenum

Trace elements such as molybdenum (Mo) are essential for the successful function of plants and animals, but deficiencies in plants are more common. Mo is normally found in agricultural soils in the range of 0.8 – 3.3 mg kg^{-1} of soil (McClaren & Cameron 1996). However, levels can vary greatly depending on the parent material and pH of the soil. Molybdenate is the primary source of molybdenum absorbed by plants and adsorption is strongly correlated with concentrations of iron (Fe) and aluminium (Al) oxides and thus soil parent material. Highly weathered soils with a low soil pH are particularly susceptible to Mo deficiency. At a low pH Mo adsorption by Al and Fe causes Mo deficiency. At a pH greater than 5.5 levels of exchangeable Al, capable of adsorbing Mo is reduced. Thus the application of lime to raise the pH will reduce the level of exchangeable Al and increase the availability of Mo (Goldburg *et al.* 1996).

Mo is an essential micronutrient for legumes to fix atmospheric nitrogen as it constituent of nitrogenase, which reduces atmospheric N_2 into plant available NH_3 (Sherrell & Metherell 1986). When Mo is deficient in the soil, successful nodulation will not occur and plants will not fix nitrogen. Mo levels are strongly related to soil pH and in most areas, Mo deficiency can be remedied by raising the pH of the soil. However, large quantities of lime can make the Mo unavailable as it is adsorbed onto the $CaCO_3$ (Gupta 1997).

2.6.2 Boron

Boron (B) is an essential trace element in all plants and it is closely associated with cell division and development in the growth regions of the plant. Since B is not readily translocated within the plant, the first visual sign of B deficiency is often the cessation of growth of terminal buds, followed by the death of young leaves and stunting of roots (Morton & Roberts 1999). B is involved in many essential plant processes including the translocation of sugars and other biochemicals, protein synthesis and nodule formation in legumes (McClaren & Cameron 1996). Since B is present in the soil predominantly as H_3BO_3 it is easily leached from the soil and deficiencies are therefore especially common on sandy soils with low organic matter and alkaline conditions. Liming therefore reduces the availability of B in the soil (Maxwell *et al.* 2012). However, the addition of lime to some soils may encourage organic matter decomposition and mineralisation of associated B, thus becoming plant available (McClaren & Cameron 1996).

2.6.3 Calcium

Calcium (Ca) is the fifth most abundant element in the earth's crust and is found in minerals such as feldspar, calcite, dolomite and appetite (McClaren & Cameron 1996). Ca is an essential macronutrient for plants and animals and is commonly added to the soil in the form of lime fertiliser ($CaCO_3$). It is found in large quantities in the leaves as a constituent of the cell wall (McClaren & Cameron 1996). Consequently, Ca has very limited mobility within the plant and cannot be translocated from older leaves to growing tissue. Thus a continuous supply of calcium is required for good plant performance. The amount of Ca available for plant uptake depends on the soil parent material and the degree of weathering that has occurred. Most soils in New Zealand contain between 0.1 and 5% Ca which exists in equilibrium in the soil solution and as exchangeable Ca^{2+} (McClaren & Cameron 1996). The amount of Ca in the soil decreases as the soil becomes more acidic and leaching losses are variable depending on the amount of rainfall, clay and humus content.

2.7 Limitations of traditional high country legumes

New Zealand high county is a challenging environment for plant growth, where soils are generally acidic with low fertility and exposed to low winter temperatures and seasonal moisture deficits (Moir & Moot 2010). These factors limit the growth and persistence of conventional forage legumes such as white clover (*Trifolium repens)*, subterranean clover (*Trifolium subterranean*) and lucerne (*Medicago satavia*).

There is currently a lack of suitable legumes able to establish and persist in the high country due to the low soil pH (pH < 5.6) and high levels of exchangeable aluminium (Moir & Moot 2010) which restricts the root growth of many legume species. High levels of aluminium ions also reduce the availability of phosphorus and calcium which is required for nodulation (Kemp *et al.* 1999). This has a direct impact on farm sustainability, productivity and profitability.

Nitrogen (N) is the key nutrient limiting plant growth in this environment, and the only supply of N is through biological fixation by legumes, as it is uneconomic to apply synthetic N fertilisers. The highly developed landscape reduces the persistence of traditional legumes, particularly due to Al toxicity and dry hot summers. By improving the soil fertility and providing adequate conditions for N_2 fixation, the total N available in the soil pool will increase, transferring directly improvements in farm profitability.

2.8 Alternative legumes

2.8.1 Tagasaste

Tagasaste also known as tree lucerne is a drought tolerant, woody, perennial legume native to the Canary Islands. Physically, the plant can reach five metres in height and three metres in diameter (Jordan 2011) if establishment and grazing management are successful. It was introduced to New Zealand and Australia in 1879 and used extensively as a fodder shrub or for land rehabilitation (Townsend & Radcliffe 1990). A visual description of this species includes soft, hairy, trifoliate leaves which produce white flowers from July through September. Seeds are brown to black in colour and mature plants have the capacity to reach 5-6 meters in height. Establishment of tagasaste is suited to lighter, free draining soils with limited competition. Townsend and Radcliffe (1987) reiterated this point and recommended direct drilling tagasaste into herbicide treated pasture and recorded successful establishment after four weeks by 18.4 and 26.9% on light and heavy soils respectively. However, large applications of herbicide may not be economic, or advisable, in hill country. Hard grazing pastures with livestock may be a more viable option to remove unwanted plant material in this environment.

Tagasaste is 'hard seeded', and as such, seeds require scarification prior to harvesting. Varied seedling rates of 1 000 – 20 000 seeds per ha have been used successfully (Snook 1982). Broadcasting seed is not recommended, as tagasaste takes a long period to establish and will be quickly out competed by other perennial grasses and legumes. Townsend and Radcliffe (1987) recorded greater establishment success with tagasaste in spring compared to summer, 47.6% and 29.3%, respectively. The yield improvements may be due to adequate root growth occurring before moisture-limiting conditions occur in summer. An additional advantage of tagasaste is its ability to retain green leaf for 3 – 5 months, much longer than for temperate grasses and legumes (Borens & Poppi 1990).

The main biological source of N in agricultural soils is through symbiotic N fixation. Bacteria of the genus *Rhizobium* invade the roots of tagasaste plants and form a root nodule within which they live and fix N_2. The plant provides the bacteria with carbohydrate for energy and the *Rhizobium* provides the plant with NH_3. Woody legume species have a relatively low potential maximum N-fixation rate up to 50 kg N ha^{-1} $year^{-1}$ (O'Connor 1969). By contrast, Scott (2003) indicated that herbaceous legumes have higher potential N-fixation rates with some fixing 600 – 800 kg N ha^{-1} $year^{-1}$. However, this trial was carried out under optimum soil conditions with low levels of organic matter, promoting maximum N_2 fixation. These glasshouse conditions may not be representative of those associated with the high country.

As mentioned, soil acidity is one of the major factors affecting the growth of pasture legumes in the high country. Soil pH affects the availability of nutrients to plants and nitrogen fixation by way of influence on the activity of rhizobia and the ability of legumes to nodulate successfully. Research has shown that tagasaste is well adapted to soils with a low pH down to a pH below 5.0 and can grow well in soils with low levels of available phosphorus, nitrogen and molybdenum (Jordan 2011; Townsend & Radcliffe 1990; Voon 1986).

There are many different species of *Rhizobium* bacteria and host plants needs to be infected with the appropriate species if fixation is to be efficient. Gault *et al.* (1994) illustrated that tagasaste formed root nodules with 20 different strains of innocula. However, uninoculated controls did not nodulate. Inoculum strains from the *Lotus* species applied to tagasaste fixed significantly more N_2 than subsequent inoculums and uninoculated plants; 12.7 mg/plant, 2.5 mg/plant and 0.6 mg/plant, respectively.

Tagasaste is highly palatable to sheep, goats and cattle (Townsend & Radcliffe 1990) and has no toxic effects on ruminants, contains no leaf tannins and has no detectable estrogenic effects on lambs (Borens 1986). Dry matter production from a trials conducted in Canterbury illustrated that tagasaste plants can generate more than 6000 kg DM/ha (2.5 kg DM/tree) (Figure 2.10) (Rickard & McBride 1986; Townsend & Radcliffe 1990). However, yields of tagasaste reported in the literature are influenced by tree planting layout and age of trees. Consequently, yields have been provided in dry matter per tree (DM/tree) in contrast to dry matter per hectare (DM/ha) to give a better understanding of the productive capacity of this legume. Radcliffe (1983) illustrated that tree spacing substantially effected yields in the first 2 – 3 years and optimum spacing between tagasaste plants within rows must depend on site conditions especially moisture and nutrient availability.

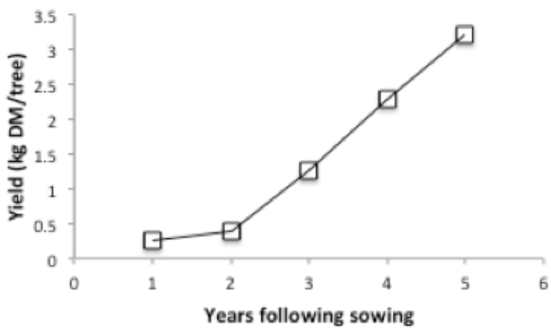


Figure 2.10 Dry matter yield of a tagasatse trial conducted under dryland conditions. Adapted from Townsend and Radcliffe (1990)

There is also rising interest in the potential of tagasaste on acidic soils. Batten (1985) showed that tagasaste is more tolerant to acidic soils than lucerne, by producing sufficient above ground biomass (1.4 kg DM/tree compared to 1.1 kg DM/tree for lucerne) in a soil with a pH of 5.0. In addition, some legumes have adapted to grow and yield well in low phosphorus conditions. In a study by Jordan (2011) tagasaste had the highest P uptake (10.0 mg P kg^{-1}) when no P fertiliser was added and the greatest 97% relative yield at the lowest P application rate (132 mg P kg^{-1}) out of 12 different annual and perennial pasture and legume species. These attributes underline the potential of different legume species in different environments: tagasaste and hairy canary may be of the most value in high country areas where is uneconomic to apply high levels of fertiliser.

In an experiment by Voon (1986) the growth response of tagasaste was investigated. There was no effect of P on the dry matter production of tagasaste. This may suggest roots were not capable of taking up applied P and growing in response to this. Tagasaste has one large main root with a few short branches, reducing the efficiency of the roots in exploring and exploiting nutrients in the soil. In contradiction to this Russell (1985) showed in a pot trial that tagasaste in a P deficient soil (Olsen P 11) increased dry matter by 150% at the application of 100 kg P/ha. Russell (1985) also found that P applications increased root production and nodulation, providing additional agronomic benefits.

The benefits of tagasaste for low input hill country systems have been illustrated by Voon (1986) and Jordan (2011). Tagasaste established and yielded better than other legume species in P deficient soils, common in this environment. P fertiliser may increase the plant height, branch number and DM yield, moreover, the real value of this legume will be in nutrient poor, highly weathered systems where competition from other pasture species and weeds is reduced.

2.8.2 Hairy Canary

Hairy canary is a perennial plant with the ability to provide stock with forage under cold, dry, low soil fertility conditions (Willis *et al.* 1989). The shrub measuring half a meter in height and one meter in diameter when mature and is highly tolerant of soil moisture deficits for prolonged periods (Wills *et al.* 2003). A visual analysis includes soft, hairy, trifoliate leaves which produce white or pink flowers from October through to December. Various studies have indicated that hairy canary has high palatability in low fertility, drought prone sites of Central Otago and the McKenzie Basin (Bell *et al.* 2005; Wills *et al.* 2003; Woodman *et al.* 1992).

This legume is also able to retain forage over winter and can provide low shelter during lambing if established in specialized forage banks. It is receiving increasing attention for regenerating low fertility, dryland sites and its survival and emergence has been examined by Douglas and Foote (1994). In this study, emergence occurred 13.7 days after sowing for nine days with 55.6% of the plant population surviving. This corresponds directly with plant survival, and in high fertility conditions, hairy canary would be vastly outcompeted by other legume and non-legume species.

In the literature, hairy canary has shown the most promise on North Island yellow/brown sands and the drier yellow/brown-grey soils of the South Island. Heavy or wet soils are not tolerated by this species (Willis *et al.* 1989). By taking advantage of limited competition in winter this woody legume has showed good productivity (5.6 t DM/ha/year) (Figure 1), high seedling numbers, and excellent survival by outcompeting species from the *Trifolium*, *Lupinus* and

Agstragalus species (Douglas & Foote 1994), especially in 'semi-arid' and drought prone environments (300 – 500 m altitude).

Willis *et al.* (1989) illustrated that inoculation failure is not a major problem for hairy canary. *Lotus (corniculatus) Rhizobium* strains are effective inoculants for hairy canary, as all plants spread some distance from the parent plant and were nodulated and healthy. It is also suggested that native plants probably utilize rhizobia associated with the *Trifolium* family.

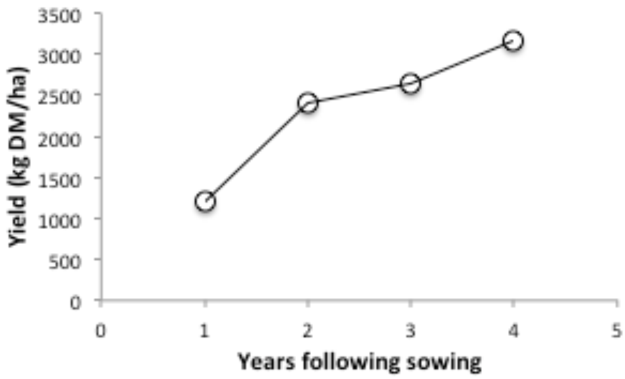


Figure 2.11 Dry matter yield of a hairy canary trial conducted under dryland conditions. Sourced from (Willis *et al.* 1989).

To date, no literature has covered the phosphorous requirements of hairy canary. However, the slow establishment of this species indicates that large fertiliser inputs or sowing in high fertility soils will result in the species being out competed at establishment and failing to survive in the pasture sward. It is suggested that additions of P will promote the growth of roots like tagasaste, but the long-term effects of P applications are not known.

2.9 Potential companion species

Tagasaste and hairy canary present a unique forage option that may provide high country farmers with increased feed quality and a shelter solution. Complete regeneration with these species is unlikely, due to the physical characteristics, maintenance and yield properties.

To maximise pasture production year round these alternative legumes would ideally be planted with companion species, which provide additional dry matter production without hindering the growth of the two legumes. From the literature, it is evident companion species should remain uncompetitive during establishment, while being able to capitalise on nitrogen fixation, and growing in conjunction with the two alternative legumes in winter and spring (Townsend & Radcliffe 1990; Willis *et al.* 1989).

Subterranean clover is an annual legume often used in areas where it is too dry for white clover and may be compatible with hairy canary and tagasaste. It germinates in autumn, grows through winter and spring, then the plant sets seed and dies in early summer to avoid drought (Costello & Costello 2003). Its ability to fix N_2 and provide high quality feed may render it useful for a pasture mixture including the herbaceous legumes and a grass species, which will take advantage of the limited competition during late summer and autumn when the legumes are predominantly inactive.

It is not recommended to sow tagasaste with annual grasses or vigorous perennial grasses such as Italian ryegrass (*Lolium multiflorum*) or cocksfoot (*Dactylis glomerata*) (White & Hodgson 1999). Establishment will be severely compromised as both these grasses are adapted to a range of environments and are extremely competitive and persistent in the early growth stages for light and soil nutrients. Tall fescue (*Festuca arundinacea*) has similar production to perennial ryegrass (*Lolium perenne*) but has greater tolerance of environmental variation such as droughts, frosts and wet periods (White & Hodgson 1999). Its slow establishment makes it a suitable match for hairy canary and tagasaste. Management considerations include endophyte causing animal health issues and grazing to minimise the presence of rank growth and seed heads, maintaining feed quality.

To maximise the productive capacity of these two legumes, sowing with grasses may be successful. Tall fescue is an alternative to perennial ryegrass and has potential in situations where summer growth is limited by lack of moisture and high soil temperatures. Its large root system also provides greater tolerance to insect pests. However, management during establishment can be critical to its success.

Complete pasture regeneration with tagasaste and hairy canary is unlikely due to establishment implications and physical growth habits. However, real value could be obtained through incorporating these legumes into high country systems in strip like plantings across the topography to provide stock protection from the elements and also a high protein feed source for stock, compared to the native grasses growing in this environment. Heavy grazing is not recommended until plants reach mature heights and limited too one or two grazing's a year during spring and summer months.

2.10 Conclusions

This review of literature has identified the current issues limiting legume growth in New Zealand high country and has attempted to identify alternative legumes which have the potential to grow successfully in this environment. The physical conditions of the high country such as climate and soils limit the productive capacity of these regions. Legumes are vital in high country pastures as the primary source of nitrogen and providing a high quality feed source. However, traditional legumes used in pastoral agriculture are not suited to this harsh environment, thus alternative legumes are sought.

Soil pH has a major effect on plants and the availability of many nutrients. The majority of high country soils have a pH below 5.5 limiting the growth capacity of many pasture species due to unavailable nutrients and toxic levels of aluminium. Application of lime generally increases pH and the availability of phosphorus and molybdenum, as well as amending aluminium toxicity allowing better access to soil moisture.

Phosphorus and sulphur are critical to maintain legume growth and persistence in the sward. Fertiliser input is usually minimal in the high country, therefore it is important to find alternative legumes to grow and yield well in soils with variable phosphate and sulphur levels. While phosphorus is important for plant growth and function very little is known about the optimum levels required for legumes while sulphur appears to be more critical for legume root growth and nodulation than providing an increase in pasture production.

Tagasaste is a perennial shrub suited to drought prone environments where it provides both high quality feed and shelter for livestock. Hairy canary provides good ground cover in low fertility soils under cold and dry conditions.

This review of literature has identified that research reporting the influence of soil fertility on the establishment and growth of Tagasaste and Hairy Canary does not exist or is very limited.

Therefore, the hypothesis of this experiment is that soil pH, exchangeable aluminium and soil fertility status will affect the establishment and growth of tagasaste and hairy canary.

As such, the objective of this study is to determine the soil fertility requirements of these two species during establishment and to evaluate the viability of tagasaste and hairy canary to establish and grow in an acid high country soil.

Chapter 3
Materials and Methods

3.1 Soil conditions

3.1.1 Soil collection and preparation

Soil was collected from a high country property, 'Armidale Station' in Central Otago, New Zealand (45º09'24.39"S, 169º51'29.30"E). The soil is a Pukerangi moderately deep silt loam, classified as an Argillic Pallic soil. The altitude is 850 m ASL with a mean annual rainfall of 450 – 500 mm. Previous fertiliser history on the site includes an application of 300 kg sulphur super in 1998, there were no further fertiliser applications until December 2011 when 250 kg of Mainland Minerals 'Mainphos' was applied to the bottom third of the block. Soil tests were performed by Ravensdown in July 2011 which indicated that pH and Olsen P were low, at 5.2 and 13 ug P mL^{-1}, respectively.

The field site was sampled on October 16 2012 (Plate 3.1). Bulk soil was collected (0 - 0.2 m depth) at several locations on the hill block. The soil was transported to Lincoln University and then passed through a 4 mm sieve (field moist) to remove all plant material. Ten sub-samples of soil were collected from the now homogenised bulk sample of field moist soil and bulked then air dried at 30ºC. Soil chemical analyses were conducted on the soil prior to treatments being added and seed sowing.

Plate 3.1 Soil collection from Armidale Station on 16 October 2012.

3.1.2 Soil chemical analysis

Soil fertility analysis were conducted on the soil from 'Armidale Station' and the results are presented in table 3.1. Soil pH was measured using a water:soil ratio of 2.5:1 (Blackmore *et al.* 1987). The method of Olsen *et al.* (1954) was used to measure available soil P, while phosphate retention was determined using the methods of both Blackmore *et al.* (1972) and Saunders (1965). The level of extractable sulphate in the soil was measured using the method of Searle (1979). Soil extractable cations were measures using the method of Schollenberger and Simon (1945), while the cation exchange capacity was determined using the method of Hesse (1971). Total carbon (C) and N contents were determined by the by the Dumas method of combustion (Horneck & Miller 1998) using an Elementar 'Vario' MAX CN Analyser (Elementar Analysensystane, GmbH). Total phosphorus concentration was determined using acid digest (Kjeldahl digest procedure (Blackmore *et al.* 1987)) and analysed for Total P concentration by molybdenum blue using FIA (Flow Injection Analyser; Tecator Inc., Sweden). Exchangeable aluminium was measured suing the 0.02 $CaCL_2$ extraction method (Edmeades *et al.* 1983) then measured by ICP-OES (Varian 720-ES ICP-OES; Varian Inc., Victoria, Australia). Reserve magnesium was determined using the method of Metson (1975) and reserve potassium was measured using the methods of Blackmore *et al.* (1972), Metson (1968) and Metson *et al.* (1956). Anaerobic mineralisable N was measured using a modified method of Waring and Bremner (1964) and Keeney and Bremner (1966).

Table 3.1 Initial average soil test results for the 'Armidale Station' Argillic Pallic soil used in this experiment.

Soil analysis	Initial value
pH	4.9
Olsen P	24 μg mL^{-1}
Sulphate Sulphur	5 μg g^{-1}
Ext. Org. Sulphur	1 μg g^{-1}
Reserve Potassium	4.73 me 100 g^{-1}
P Retention	41%
Anaerobic MinN	130 kg ha^{-1}
Organic Matter	7.1% w/w
Exchangeable Aluminium	15.7 mg kg^{-1}
Total Nitrogen	0.27% w/w
Total Carbon	4.15% w/w
Carbon/Nitrogen	15:0.1
Resin P	41 mg kg^{-1}
CEC	16 me 100 g^{-1}
Calcium	2.7 me 100 g^{-1}
Magnesium	0.96 me 100 g^{-1}
Potassium	0.65 me 100 g^{-1}
Sodium	0.22 me 100 g^{-1}
Base Saturation (Total)	29.2%

3.2 Experimental design and trial management

3.2.1 Trial design and setup

The pot trial was conducted at the Horticulture nursery, Lincoln University. Pots were sown in February 2014 and remained outside in a caged area on tables until they were moved into the glasshouse at the end of April 2014. The pot trial examined two species of pastoral legumes for alternative use in the high country; Tagasaste (*Chamaecytisus palmensis*) and Hairy Canary (*Dorycnium hirsutum*). A pasture mixture was also sown to determine the effects of competition from a grass species (Cocksfoot, *Dactylis glomerata*) on hairy canary and tagasaste and also included lucerne with the two species.

Table 3.2 Experimental design outlining different treatment levels for tagasaste and hairy canary.

	P0	**P1**	**P2**	**P3**
L0	L0P0(-S)	L0P1	L0P2	L0P3
L1	L1P0	L1P1	L1P2	L1P3
L2	L2P0	L2P1	L2P2	L2P3
L3	L3P0	L3P1	L3P2	L3P3
-S	L2P0	L2P1	L2P2	L2P3
ALL		Complete + T.E (L2)		

Table 3.3 Experimental design outlining different treatment levels for the cocksfoot, lucerne, tagasaste and hairy canary mixture.

	L0	L1	L2	L3
0P	L0P0	L0P0	L0P0	L0P0
P3	L0P3	L1P3	L2P3	L3P3
P3 + S	L0P3S	L1P3S	L2P3S	L3P3S
ALL	Complete + T. E. (L2)			

Table 3.4 Treatment codes and nutrient rates used in this experiment.

Treatment code	Nutrient	Nutrient rate
L0	Lime	0 kg lime ha^{-1}
L1	Lime	2000 kg lime ha^{-1}
L2	Lime	4000 kg lime ha^{-1}
L3	Lime	8000 kg lime ha^{-1}
P0	Phosphorus	0 mg P kg^{-1} soil
P1	Phosphorus	50 mg P kg^{-1} soil
P2	Phosphorus	150 mg P kg^{-1} soil
P3	Phosphorus	500 mg P kg^{-1} soil
-S	Sulphur	0 kg S ha^{-1}
S	Sulphur	120 kg S ha^{-1}

A fully factorial design was used with each species subjected to 22 treatments as shown in Table 3.2. Each treatment was replicated four times to give a total of 176 pots. The Cocksfoot mixture was subjected to 13 treatments in a replicative subtractive design as shown in Table 3.3. Each treatment was replicated four times to give an additional 52 pots. Overall there was a total of 228 pots.

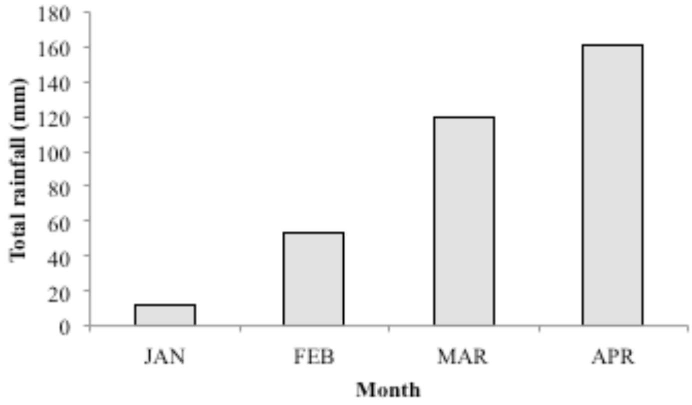
Large pots, 5 L in volume were used. Field soil (4 L) was measured for each pot and placed into a plastic bag. The appropriate lime, phosphorus and sulphur treatment was weighed and added to the bag, where it was shaken thoroughly to get an even distribution of treatment nutrients throughout the soil. The bag was then emptied into the associated pot and labelled. These pots were then placed outside on tables in a caged area and water *ad libitium*. The final soil surface was approximately 40 mm below the top of the pot.

3.2.2 Outside cage conditions

The establishment period of this trial occurred outside in a caged area at the Lincoln University Horticultural Nursery. Pots were placed on tables to ensure that no damage occurred from rabbits or other pests which could damage plants when at ground level. By incorporating a period where plants are exposed to natural environmental conditions, wind, rain and humidity, conditions were a better representation of how these plants would establish and grow in a natural environment.

Plate 3.2 Pot trial located in the caged area at the Horticulture Nursery, Lincon University on 26 March 2014.

(a)



(b)

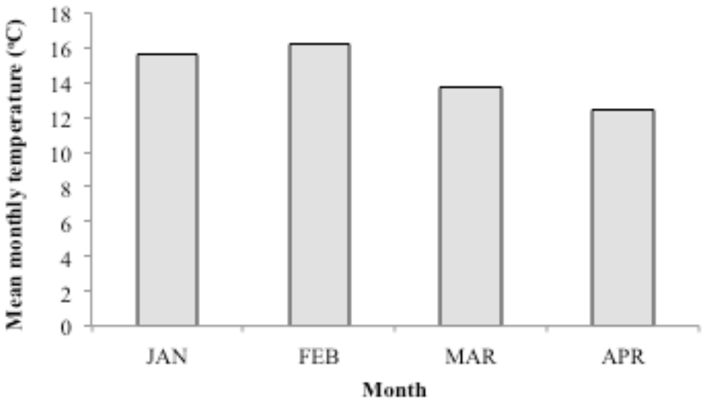


Figure 3.1 (a) Total monthly rainfall (mm) and (b) mean monthly temperature at Broadfields Station located 2.5km North of Lincoln University during the outside trial period.

3.2.3 Glasshouse conditions

Pots were moved into Forrester glasshouse, located at the Lincoln University Horticultural Nursery in mid-April to allow continued growth over the winter months. The glasshouse was heated, with the temperature constantly monitored inside the glasshouse during the trial period. The mean daily temperature inside the glasshouse for the duration of the trial was 18.5^{o}C, with the minimum and maximum recorded temperatures being 8.2 and 28.8^{o}C, respectively.

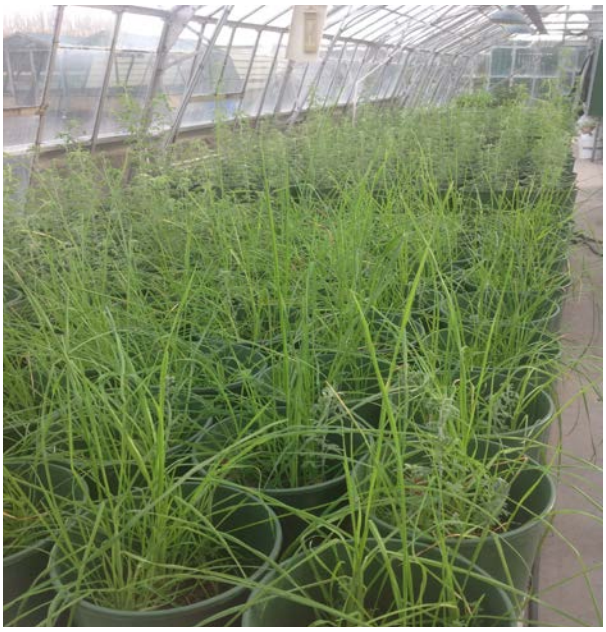


Plate 3.3 Pot trial set up in Forrestor Glasshouse, Horticulture Nursery, Lincoln University on 15 April 2014.

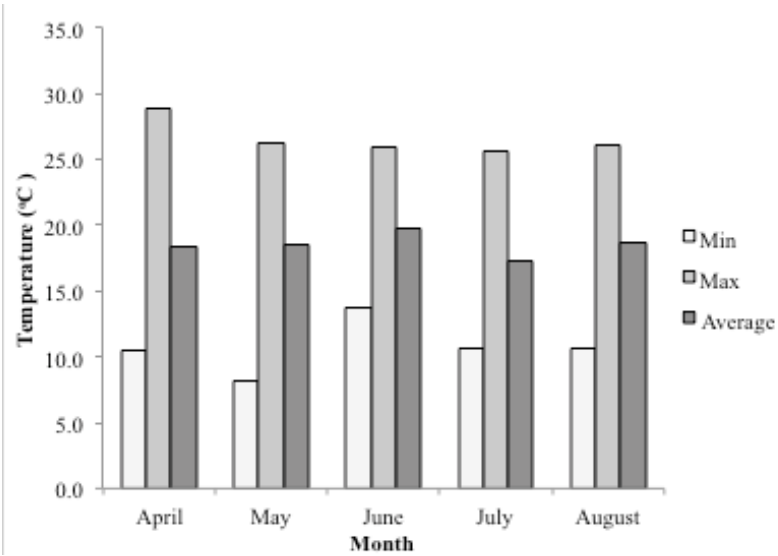


Figure 3.2 Average, minimum and maximum monthly temperature (°C) at Forrestor Glasshouse, Horticulture Nursery, Lincoln University for the period April 2014 to August 2014.

3.2.4 Plant establishment

Seeds were initially sown at 10 seeds per pot on the 7th February at a depth of 0.3 – 0.5 cm below the soil surface. Plants were later thinned to a final density of six plants per pot. The plants were arranged in their species and were watered regularly during the establishment phase. The legumes examined were:

- Tagasaste (*Chamaecytisus palmensis*)
- Hairy Canary (*Dorycnium hirsutum*)

The tagasaste seeds were scarified prior to sowing by immersing the seed in boiling water for ten minutes, rinsed and then exposed to a rough surface and agitated for a further five minutes. Some tagasaste plants which failed to emerge were re-sown with pre-germinated seedlings soon after the initial sowing. All pots were thinned to the final plant density of 6 plants per pot on the 17th March 2014. All seeds used in the experiment were uncoated (no lime and/or trace element coating).

3.2.5 Inoculation

The pots were inoculated with commercial lotus rhizobia strains (‘Nodulaid’, Becker Underwood Ltd, Australia) on the 19th March. A small amount of peat inoculum was mixed to form a slurry and the appropriate rhizobia strain (group ‘D’) was added to the slurry and then applied to both legume species.

3.2.6 Pot management

The pots were weeded throughout the experiment to ensure the plants under investigation were free from inter-specific competition. Plant counts were carried out throughout the experiment and any pots with plants missing were sown with new seeds and the pot number noted. All plants were monitored on a weekly basis to limit the occurrence of disease or excess water application.

3.2.7 Basal nutrient application

Basal nutrient solution was applied to the ‘ALL’ treatment on two occasions in mid-February and mid-April. The solution applied was a ‘complete treatment’ containing all macro and trace elements required for plant growth.

Table 3.5 The constituent type and amount in each solution used in the complete nutrient treatment.

Solution	Constituents included	Amount
Solution A (g/4 L)	KH_2PO_4	12 g
	K_2HPO_4	13.06 g
	K_2SO_4	8.88 g
Solution B (g/4 L)	$MgCl_2\ 6H_2O$	8.08 g
	$CaCO_3$	2.04 g
	HCL	40 mL
	Na_2SO_4	6.22 g
Trace Element (g/L)	H_3BO_3	0.03 g
	$CoCl_2\ 6H_2O$	0.004 g
	$CuCl_2\ 2H_2O$	0.01 g
	$MnCl_2\ 4H_2O$	0.2 g
	$(NH_4)6Mo_7O_{24}4H_2O$	0.004 g
	$ZnCl_2$	0.015 g
Ferric Citrate	0.0585 g FE citrate/L water	

The complete nutrient treatment contained:

- 490 mL of Solution A
- 490 mL of Solution B
- 49 mL of Trace Element Solution
- 28 mL of Fe Citrate Solution

This mixture was made up to 10 L with distilled water and then 210 mL was applied to each pot receiving the complete nutrient treatment. In addition to the basal nutrient solution, 300 kg ha^{-1} of elemental sulphur ('Tiger 90' elemental sulphur prills) was added to each pot excluding the control on the 10^{th} April 2014.

3.2.8 Soil moisture and watering management

Pots were watered as required (usually every 1-3 days) to maintain a consistent volumetric water content of 35-40% which represented a soil which was neither waterlogged nor dry. During the period of the experiment which the plants were outside lower temperatures and rainfall events resulted in slower plant growth and thus, less watering. In the glasshouse the temperature fluctuated less and remained warm over the winter months. Watering took place several times a week in this environment to ensure moisture levels were adequate for continued plant growth.

3.3 Measurements

3.3.1 Dry matter yield

Plants were harvested every four to five weeks, so as to maximise shoot yield but prevent plants from becoming reproductive (flowering). A total of five harvests were performed on the 7th April, 13th May, 6th June, 14th July and the 13th of August.

For both legume species a representative plant was selected and gently extracted from the soil with the shoot and root intact. Following harvesting the separated shoots and roots were placed in paper bags and oven dried at 70^{o}C for 72 hours. All herbage samples were then weighed on a two decimal place balance to obtain the dry weight (g DM plant^{-1}). This represented the shoot and root DM yield for the given growth period.

Plate 3.4 Harvesting hairy canary, 13 August 2014

3.3.2 Length measurements

Upon extraction from the soil, shoot lengths were measured and separated from the roots, which were washed and the corresponding length measured.

3.3.3 Nodule score

Nodule scoring was carried out during each harvest to quantify the ability of these legumes to successfully produce nodules required for nitrogen fixation. Roots were separated from the shoots, washed and observed for nodules. Approximately 5% of the total soil was lost during this process as it clung to the roots and was removed during washing. During this process nodules fell off the roots, however this was consistent across all of the samples. Samples were always placed in the fridge between washing and nodule scoring. The nodules were scored using an adapted version of the Peoples *et al.* (1989) nodule scoring criteria. It was assumed during the process that pigmented nodules were active and any green or white nodules were inactive, however this was not tested due to time constraints. Each of the plants from a treatment were examined and given a nodule score.

Table 3.6 Nodule scoring system used during the assessment of Tagasaste and Hairy Canary nodules on the roots (Adapted from Peoples et al. (1989).

Number of pigmented nodules	Nodule score
> 20	5
> 15	4
> 10	3
> 5	2
< 5	1
No pigmented nodules	0

Each nodules score corresponded to a different ability to biologically fix nitrogen which is shown in Table 3.7.

Table 3.7 interpreting nodule scores for Tagasaste and Hairy Canary (Adapted from Peoples et al. (1989).

Nodule score	Ability to fix nitrogen
4-5	Excellent nodulation and potential to fix N
2-3	Fair nodulation, N fixation may not be sufficient to provide crop N demand
0-1	Represents poor or no nitrogen fixation

It is important to note that this is a visual guide only and could be proven through testing in the laboratory for populations of active rhizobia present in the nodules using Acetylene reduction tests. Nodulation and in some cases root growth of the two species was prolific, however sometimes very few nodules were pink indicating that they were inactive. The size of the nodules varied from 0.5 mm to 5 mm and some large nodules were usually unshaped.

3.3.4 Plant tissue analysis

The herbage samples from the final two harvests were bulked on an individual pot basis and had the stems and roots removed before the leaves were finely ground using a Retsch grinder. Bulked samples were placed into plastic vials and underwent nutrient analysis.

The plant samples were acid digested using the following method; 0.5 g of dried, ground sample was put in a microwave vessel, the exact weight was recorded. The sample was then digested in 2.5 mL nitric acid (HNO_3) and 2.5 mL of 30% hydrogen peroxide (H_2O_2). The vessel was sealed and vortexed to ensure the acids and sample were well mixed. The vessels were then loaded into the turntable and placed into the microwave cavity. The plant digest programme consists of samples being increased to 90°C over 15 minutes, and then up to 180°C over 10 minutes. Once cooled the samples were made up to 25 mL using MiliQ water. Digest samples were analysed for a complete range of elements (excluding N) using inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) analysis (Varian 720-ES ICP-OES; Varian Inc., Victoria Australia).

3.3.5 Final soil sampling

One soil core (25 mm diameter X 75 mm long) was taken from each pot on August 28th and cores bulked on a treatment basis. The soil was dried at 30°C for seven days and then underwent basic analysis (pH, Olsen P, sulphate and sulphur) at the commercial lab, ARL (Napier). The range of soil analysis and procedures carried out were similar to those outlined in section 3.1.2.

Table 3.8 Average soil test results for the Armidale Station soil across the individual lime, phosphorus and sulphur treatments.

Treatment	pH	Olsen Sol. P (µg mL)	Sulphate sulphur (µg mL)
Control	5.1	14	4
L0	4.4	68	144
L1	5.0	63	105
L2	5.4	59	219
L3	6.5	59	192
P0	5.2	17	118
P1	5.3	30	129
P2	5.2	58	112
P3	5.2	134	142
-S	5.4	60	235

Plate 3.5 Soil sampling pots with 75 mm mm soil corer, August 28th 2014.

3.4 Statistical analysis

Dry matter yield, physical measurements, nodule scores and herbage data will be statistically analysed using Genstat version 14.0 (VSN International), analysis of variance (ANOVA) with the S0 and ALL treatments excluded to determine if lime or P was significant in terms of yields, length measurements, nodule score and nutrient concentrations within each species. A Fischer's protected LSD was carried out and three T-tests (individual treatment contrasts) which examined the sulphur effect, pH effect and if the ALL treatment was different to L2P3. This was also to include the treatments which were excluded from the ANOVA to determine significance.

Chapter 4
Results

Sections 4.1 to 4.4 report results of dry matter yield, shoot and root lengths, nodulation and nutrient concentrations for tagasaste, hairy canary and the cocksfoot and the legume mixture.

4.1 Yield

The total DM yield of tagasaste was significantly ($P < 0.05$) affected by lime rate (Table 4.1). The yield increased from 2.32 (0 t lime/ha) to a maximum of 3.26 (4 t lime/ha). The DM yield increased by 0.23 g DM/pot per t lime/ha applied to the soil. Yield then declined above the lime rate of 4 t ha^{-1}. A rate of 8 t lime/ha gave a total DM yield of 3.07 g DM/pot. Mean winter shoot yield exceeded autumn yield and was significantly ($P < 0.05$) affected by lime applied. DM yield increased by 0.24 g DM/pot up to 4 t lime/ha with the additional 4 t lime/ha only accounting for a 0.02 g DM/ha increase. Total root yield was strongly influenced by lime rate ($P < 0.01$) with DM peaking at 0.69 g DM/pot. This represented a steady increase in yield between 0 and 4 t lime/ha applied followed by a decline at 8 t lime/ha.

Hairy canary also yielded the highest total dry matter yield at 4 t lime/ha of 4.32 g DM/pot (table 4.2). There was a highly significant difference ($P < 0.001$) in shoot yields across the lime rates for this species. Between 0 (3.34 g DM/pot) and 4 t lime/ha applied the yield increased by 0.25 g DM/pot. A decline in yield was observed above the lime rate of 4 t ha^{-1} of 0.25 g DM/pot per t lime applied. P applied to the soil had no significant ($P > 0.05$) DM yield response for tagasaste and hairy canary.

Overall, hairy canary was the highest yielding species ($P < 0.001$), which was very strongly affected by lime rate ($P < 0.001$). Both species exhibited maximum yields at the lime rate of 4 t/ha^{-1} ($P < 0.001$). On a per harvest basis, total yield increased linearly for each species as each harvest progressed, with the greatest dry matter yield achieved at the last harvest (Appendix 1). The greatest yield response was observed over the last growing period where dry matter increased by over 300% in some cases.

Tagasaste and hairy canary showed a significant lime x P interaction ($P < 0.05$) for total shoot DM yield. This interaction was consistent for the winter shoot yield for tagasaste. Whereas during the autumn growth period no response was observed. Hairy canary had an observed highest total shoot DM at a lime rate of 4 t ha^{-1} and a phosphorus rate of 500 mg kg^{-1}. Hairy canary also observed highest yields at the same application rates of lime and phosphorus. There were no other Lime x P interactions observed in the data.

Table 4.1 Shoot and root yield of Tagasaste (Chamaecytisus palmensis) grown under a controlled extrenal environment and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha)and increasing rates of P (four levels ranging from 0 – 500 mg P/kg soil).

	Yield (g DM/pot)			
Tagasaste	**Autumn shoot yield**	**Winter shoot yield**	**Total shoot yield**	**Total root yield**
Lime rate (t/ha)				
0	0.20	2.12	2.32	0.38
2	0.22	2.85	3.07	0.57
4	0.22	3.05	3.26	0.69
8	0.19	3.07	3.25	0.53
SEM	0.02	0.36	0.37	0.08
LSD (5%)	0.05	0.72	0.75	0.16
P value	ns	*	*	**
P rate (mg/kg)				
0	0.18	2.41	2.59	0.46
50	0.22	3.14	3.37	0.61
150	0.22	2.46	2.67	0.51
500	0.20	3.08	3.27	0.59
SEM	0.03	0.37	0.39	0.09
LSD (5%)	0.05	0.73	0.76	0.18
P value	ns	ns	ns	ns
Grand mean	0.21	2.77	2.98	0.54
SEM	0.05	0.73	0.76	0.17
LSD (5%)	0.10	1.45	1.51	0.34
Lime x P interaction	ns	*	*	ns
Contrasts:				
ALL V.s L2P3	***	***	***	***
L0P0 V.s L0P0-S	***	***	***	***
L0P0-S V.s L2P0-S	***	***	***	***

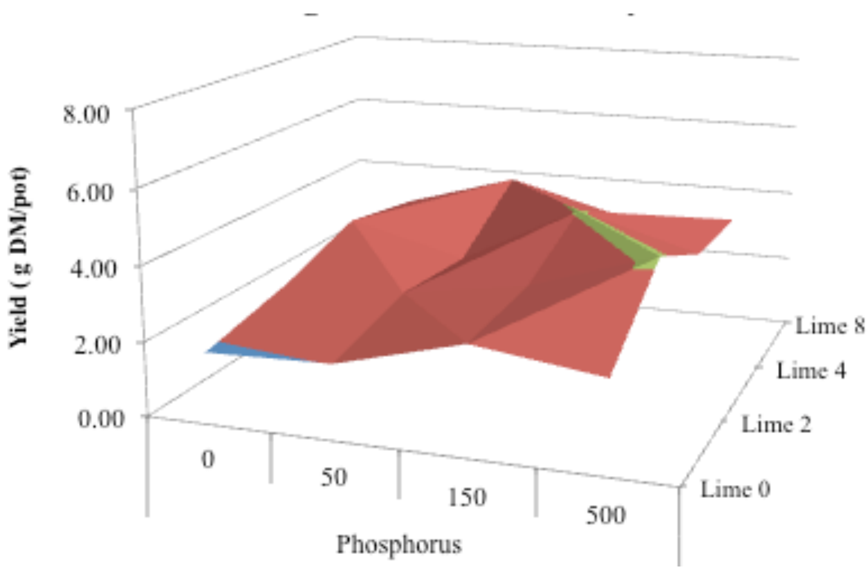
*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

Table 4.2 Shoot and root yield for Hairy canary (Dorycnium hirsutum) grown under glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) and increasing rates of P (four levels ranging from 0 – 500 mg P/kg soil).

	Yield (g DM/pot)			
Hairy Canary	**Autumn shoot yield**	**Winter shoot yield**	**Total shoot yield**	**Total root yield**
Lime rate (t/ha)				
0	0.14	3.20	3.34	0.78
2	0.20	3.85	4.05	0.90
4	0.15	4.17	4.32	0.92
8	0.14	3.23	3.37	0.71
SEM	0.02	0.26	0.27	0.08
LSD (5%)	0.04	0.53	0.54	0.15
P value	***	***	***	*
P rate (mg/kg)				
0	0.15	3.46	3.62	0.84
50	0.15	3.73	3.89	0.86
150	0.14	3.36	3.50	0.75
500	0.18	3.90	4.08	0.86
SEM	0.02	0.29	0.30	0.08
LSD (5%)	0.04	0.59	0.60	0.16
P value	ns	ns	ns	ns
Grand mean	0.16	3.61	3.77	0.83
SEM	0.04	0.55	0.57	0.16
LSD (5%)	0.08	1.08	1.14	0.31
Lime x P interaction	ns	ns	*	ns
Contrasts:				
ALL V.s L2P3	***	***	***	***
L0P0 V.s L0P0-S	***	***	***	***
L0P0-S V.s L2P0-S	***	***	***	***

*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

a)



b)

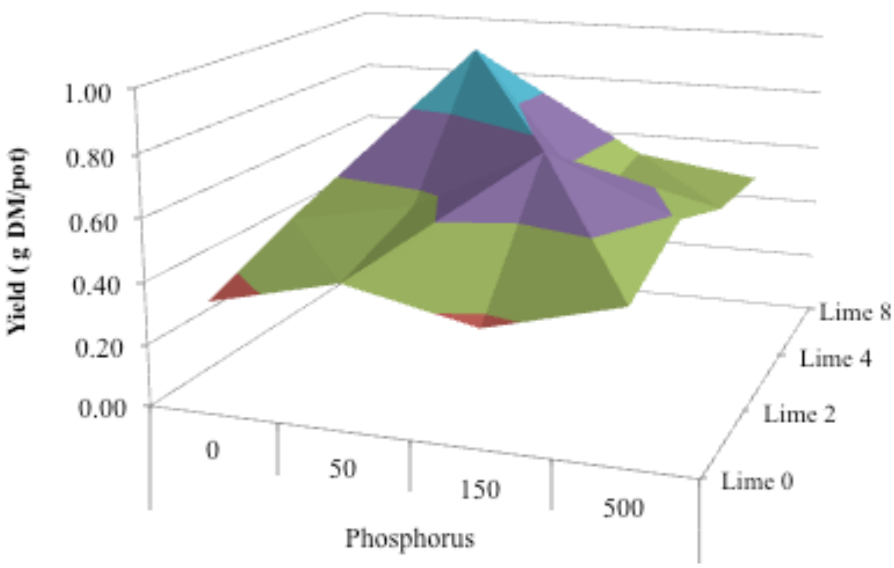
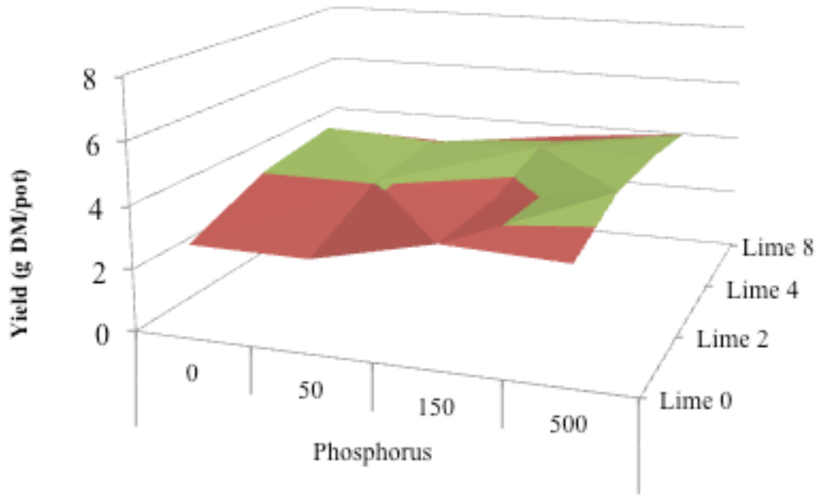


Figure 4.1 Total accumulate shoot (a) and root dry (b) matter (DM) response of tagasaste to increasing levels of applied lime (four levels ranging from 0 – 8 t lime/ha) and increasing levels of phosphorus (levels 0 and 500 mg P/kg soil).

a)



b)

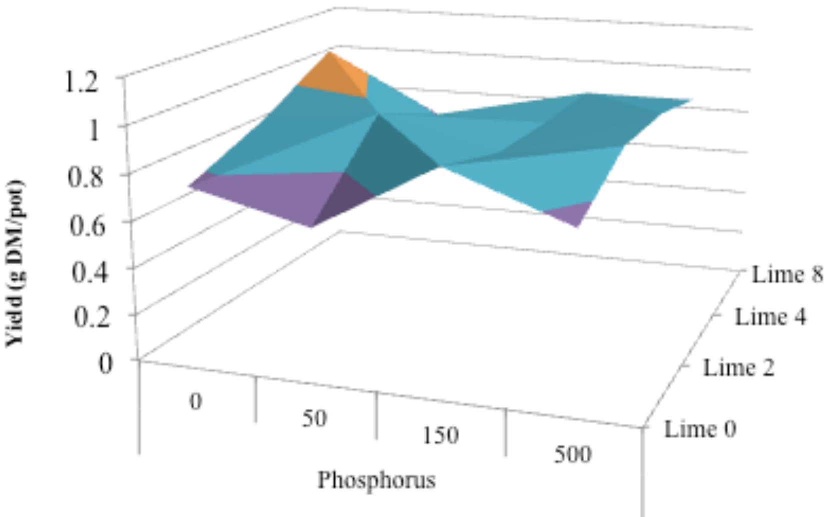


Figure 4.2 Total accumulate shoot (a) and root dry (b) matter (DM) response of hairy canary to increasing levels of applied lime (four levels ranging from 0 – 8 t lime/ha) and increasing levels of phosphorus (levels 0 and 500 mg P/kg soil).

4.2 Shoot and root length

Tagasaste winter shoot length was affected (*P* < 0.01) by P rate. The shoot length increased with P applied up to 500 mg/kg at 455 mm (Table 4.3). There was an increase in total shoot length (*P* < 0.01) from 468 mm with 0 mg/kg applied to 568 mm with 500 mg/kg applied. Autumn root length showed a significant (*P* < 0.01) response to increasing lime applications. Root length was affected by P rate (*P* < 0.01) and peaked at 142 mm at 500 mg/kg applied, which is the equivalent of 20 mm per 100 mg/kg of P applied. Total root length increased with an increase in applied lime to a maximum length of 257 mm at 4 t lime/ha. Between 4 and 8 t lime/ha applied total root length decreased by the equivalent of 3.6 mm per t lime applied.

There was a strong and significant (*P* < 0.01) winter shoot length response for hairy canary with increased lime. The shoot length increased between 0 and 4 t lime/ha applied at which the shoot length peaked at 818 mm. The yield declined by 16 mm for every t lime applied between 4 and 8 t lime/ha (Table 4.4). An increase in lime application resulted in an increase in total shoot length up to 4 t lime/ha applied at 468 mm. Autumn shoot length was affected by increasing lime rate up to 2 t lime/ha (*P* < 0.05). Additional lime applied decreased root length to 173 mm. An increase in phosphorus rate resulted in no significant (*P* > 0.05) difference in the autumn, winter or total measurement response of hairy canary.

The application of 120 kg S/ha of applied sulphur (gypsum) had a very highly significant (*P* < 0.001) effect on shoot and root lengths for tagasaste and hairy canary. Sulphur increased shoot lengths of tagasaste and hairy canary from 429 mm to 508 mm and 354 mm to 376 mm, respectively. Root lengths also increased for the two species, from 248 mm to 347 mm and 363 mm to 631 mm for tagasaste and hairy canary, respectively, when S was applied.

Successive harvest measurements give an indication of the growth pattern of tagasaste and hairy canary. The initial growth period (harvest 1 and 2) represents the development stage where tagasaste growth was slow followed by an exponential growth period between harvest three and four which saw shoot length increase by 285% in a one month period (Figure 4.3 and Appendix 1). Root growth followed the same pattern experiencing maximum lengths in the later part of the trial (Figure 4.3 and Appendix 1). In contrast, hairy canary root lengths were larger than tagasaste, peaking at 235 mm at harvest five. Shoot growth only exceeded root growth in the last growing period.

Table 4.3 Shoot and root measurements for tagasaste (Chamaecytisus palmensis) grown under controlled external conditions and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) and increasing rates of P (four levels ranging from 0 – 500 mg P/kg soil).

	Length (mm)					
Tagasaste	**Autumn shoot length**	**Winter shoot length**	**Total shoot length**	**Autumn root length**	**Winter root length**	**Total root length**
Lime rate (t/ha)						
0	101	388	489	107	326	217
2	120	418	537	125	366	246
4	110	418	528	135	380	257
8	112	415	527	142	344	243
SEM	8.62	30.0	38.6	10.3	27.0	14.7
LSD (5%)	17.2	60.1	77.3	20.7	54.1	29.4
P value	ns	ns	ns	**	ns	*
P rate (mg/kg)						
0	98.6	388	468	117	354	236
50	118	445	562	135	370	253
150	113	369	482	129	345	237
500	113	442	558	128	347	237
SEM	8.55	28.2	35.5	11.1	27.9	15.5
LSD (5%)	17.1	56.7	74.1	22.3	55.7	31.0
P rate	ns	**	**	ns	ns	ns
Grand mean	111	409	520	127	354	241
SEM	17.2	58.2	74.1	21.4	54.9	30.2
LSD (5%)	34.3	116.8	151.4	43	110	60.4
Lime x P interaction	ns	ns	ns	ns	ns	ns
Contrasts:						
ALL V.s L2P3	***	***	***	***	***	***
L0P0 V.s L0P0-S	***	***	***	***	***	***
L0P0-S V.s L2P0-S	***	***	***	***	***	***

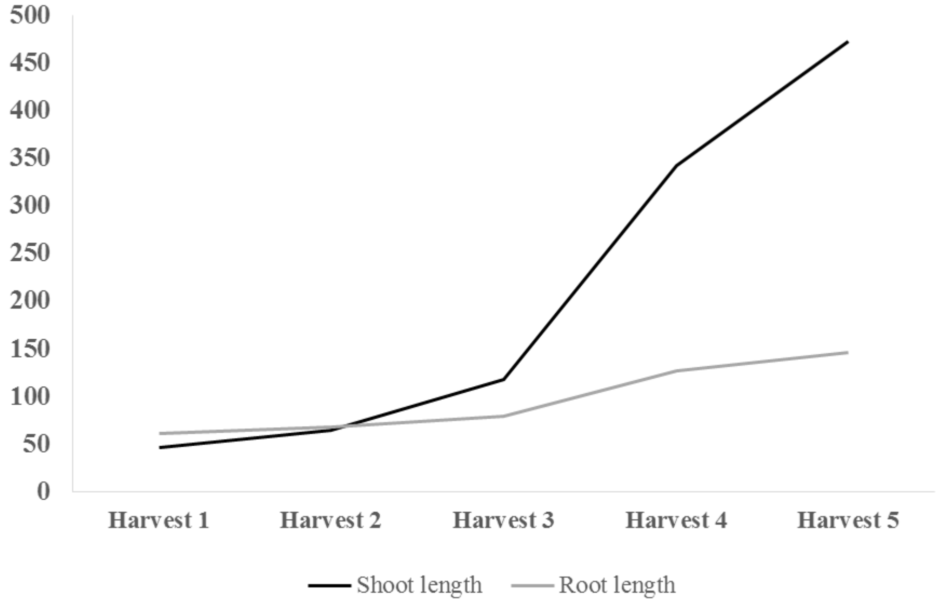
*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

Table 4.4 Shoot and root measurements for hairy canary (Dorycnium hirsutum) grown under controlled external conditions and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) and increasing rates of P (four levels ranging from 0 – 500 mg P/kg soil).

	Length (mm)					
Hairy Canary	**Autumn shoot length**	**Winter shoot length**	**Total shoot length**	**Autumn root length**	**Winter root length**	**Total root length**
Lime rate (t/ha)						
0	114	709	412	185	515	350
2	115	798	457	198	520	359
4	118	818	468	193	513	353
8	120	754	437	173	532	353
SEM	6.48	33.6	17.9	8.98	60.1	30
LSD (5%)	12.9	67.3	35.8	17.9	120	60
P value	ns	**	**	*	ns	ns
P rate (mg/kg)						
0	113	749	431	181	512	347
50	117	760	439	196	472	334
150	112	755	434	188	599	394
500	125	816	470	184	495	340
SEM	6.25	35.6	18.7	9.36	57.5	28.8
LSD (5%)	12.5	71.3	37.3	18.8	115	57.6
P rate	ns	ns	ns	ns	ns	ns
Grand mean	117	770	444	188	520	354
SEM	12.73	69.2	36.6	17.34	117.6	58.8
LSD (5%)	25.4	138.6	73.1	36.7	235	119
Lime x P interaction	ns	ns	ns	ns	ns	ns
Contrasts:						
ALL V.s L2P3	***	***	***	***	***	***
L0P0 V.s L0P0-S	***	***	***	***	***	***
L0P0-S V.s L2P0-S	***	***	***	***	***	***

*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

a)



b)

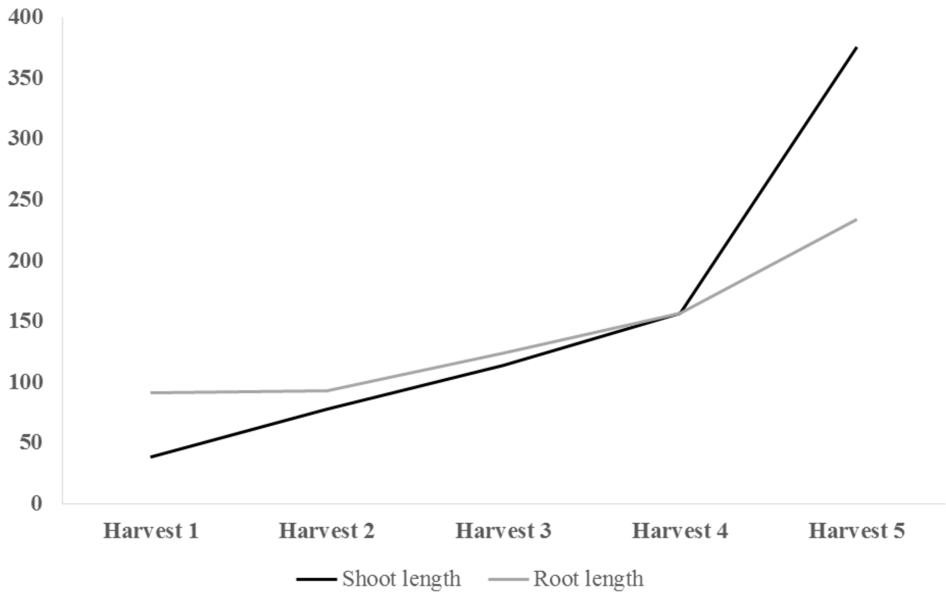


Figure 4.3 Average shoot and root growth of tagasaste (a) and hairy canary (b) grown in a high country soil as per harvest basis.

4.3 Nodulation

The autumn nodulation of tagasaste was significantly ($P < 0.05$) influenced by lime rate (Table 4.5). Autumn nodule score peaked at 8 t lime/ha with a score of 2.16. The lowest level of nodulation occurred at the application rate of 0 t lime/ha. Winter nodulation was maximised at a score of 2.98 at 2 t lime/ha. Between the applications of 2 and 8 t lime/ha the winter nodule scores were reduced by 0.08 per t lime applied. On a per harvest basis, nodulation followed no trend for the first three harvests. However, an increase was observed in the last two periods which showed with a greater proportion of high nodule scores (a score > 3) as seen in Appendix 1. Phosphorus applications did not affect autumn nodulation of tagasaste or hairy canary. However, winter nodulation of hairy canary was strongly affected by P rate. Nodule scores increased with applied P up to 500 mg/kg at 2.71.

Table 4.5 Nodulation scores for tagasaste and hairy canary grown under glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) and increasing rates of P (four levels ranging from 0 – 500 mg P/kg soil).

	Tagasaste		**Hairy Canary**	
	Autumn nodule score	Winter nodule score	Autumn nodule score	Winter nodule score
Lime rate (t/ha)				
0	1.50	2.31	1.38	2.23
2	1.97	2.98	1.31	2.41
4	2.00	2.46	1.28	2.44
8	2.16	2.48	1.34	2.38
SEM	0.23	0.24	0.14	0.17
LSD (5%)	0.47	0.48	0.28	0.34
P value	*	*	ns	ns
P rate (mg/kg)				
0	1.88	2.46	1.19	2.15
50	2.00	2.67	1.32	2.30
150	1.81	2.48	1.34	2.38
500	1.94	2.63	1.47	2.71
SEM	0.25	0.25	0.14	0.15
LSD (5%)	0.50	0.51	0.27	0.31
P rate	ns	ns	ns	**
Grand mean	1.91	2.56	1.33	2.37
SEM	0.47	0.49	0.28	0.32
LSD (5%)	0.97	0.99	0.56	0.66
Lime x P interaction	ns	ns	ns	ns
Contrasts:				
ALL V.s L2P3	***	***	***	***
L0P0 V.s L0P0-S	***	***	***	***
L0P0-S V.s L2P0-S	***	***	***	***

*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

4.4 Herbage nutrient concentrations

Results presented in this section represent analysis conducted on winter herbage samples.

4.4.1 Herbage phosphorus

Lime had no significant influence on the concentration of P in the herbage of tagasaste ($P > 0.05$). The increased application of phosphorus significantly ($P < 0.001$) influenced the phosphorus concentration of tagasaste herbage. Maximum herbage P concentrations were obtained at the highest level of applied P, 500 mg P/kg (263 mg P/kg; Table 4.6).

Hairy canary herbage P concentrations were strongly influenced by lime ($P < 0.01$). The P concentration reduced between 0 and 2 t lime/ha applied to 221 mg P/kg (Table 4.7). Maximum P herbage concentrations were detected at the application rate of 8 t /ha^{-1} at (361 mg P/kg). Increasing the phosphorus rate resulted in no significant ($P > 0.05$) difference in the herbage P concentration of hairy canary.

The application of 120 kg S/ha of applied sulphur (gypsum) increased ($P < 0.001$) the phosphorus herbage concentration for both species.

4.4.2 Herbage sulphur

Increasing the lime rate had a strongly significant effect ($P < 0.001$) on the sulphur herbage levels of tagasaste (Table 4.6). There was an initial reduction in herbage S concentration from 0 to 2 t lime/ha applied (at 119 mg S/kg). The maximum herbage S concentration of 159 mg S/kg was observed at the application rate of 4 t lime/ha. Hairy canary S levels were affected ($P < 0.05$) by lime rate with a peak concentration of 518 mg S/kg at the application rate of 150 mg P/kg (Table 4.7).

Increased P application had no significant ($P > 0.05$) effect on sulphur concentration in the herbage of tagasaste or hairy canary. The application of 120 kg S/ha of sulphur (gypsum) had a highly significant ($P < 0.01$) and significant ($P < 0.05$) effect on the sulphur herbage concentration for tagasaste and hairy canary, respectively.

4.4.3 Herbage molybdenum

Tagasaste herbage Mo concentration was significantly ($P > 0.05$) increased by lime rate. Lime application very significantly ($P > 0.001$) influenced the Mo concentration in hairy canary (Table 4.7). Mo levels increased to a concentration of 0.251 mg/kg at 8 t lime/ha. Tagasaste and hairy canary herbage Mo concentration was not significantly ($P > 0.05$) affected by the rate of P applied.

4.4.4 Herbage manganese

Tagasaste herbage manganese levels were strongly influenced by lime rate (*P* < 0.001). The Mn concentration peaked at 0 t lime/ha of 366.7 mg/kg of plant material (Table 4.6). There was a steady decrease in the herbage Mn concentration with increasing lime rates the lowest concentration of 48 mg/kg occurring at the highest lime rate applied. Lime rate had a highly significant effect (*P* < 0.001) on the herbage Mn concentrations of hairy canary. Similar to hairy canary, tagasaste Mn rates decreased from 362.8 mg/kg at 0 mg/kg to 34.4 mg/kg at 8 t lime/ha.

Herbage manganese concentrations of tagasaste and hairy canary were not significantly (*P* > 0.05) affected by P rate. The application of 120 kg S/ha of applied sulphur (gypsum) had a highly significant (*P* < 0.01) and very highly significant (*P* < 0.001) effect, increasing the molybdenum herbage concentration for tagasaste and hairy canary.

4.4.5 Herbage boron

Lime rate had a very highly significant effect (*P* < 0.001) on tagasaste mean shoot boron concentrations (Table 4.6). B levels peaked at 2 t lime/ha at 19.0 mg/kg. Between 2 and 8 t lime/ha B concentration decreased by 1.23 mg/kg per t of lime applied. This trend is highlighted in Figure 4.1 (a) which shows boron across both species decreased with an increase in pH which resulted from lime application. Similarly, a reduction in B concentration in hairy canary was also observed from 51.6 at 0 t lime/ha to 40.6 at 8 t lime/ha (Table 4.7). The relationship between herbage B concentration in hairy canary and lime rate is evident with a probability of *P* < 0.05.

Phosphorus rate had a strong (*P* < 0.01) influence on the herbage B concentration of hairy canary. The maximum B level was observed at a P rate of 500 mg/kg and declined by 2.5 mg/kg per t lime applied. There was no significant (*P* > 0.05) response observed in boron concentration with applied P. The application of 120 kg S/ha of applied sulphur (gypsum) had a highly significant effect (*P* < 0.001) on the boron herbage concentration for both species.

4.4.6 Herbage aluminium

Herbage aluminium concentration ions of tagasaste and hairy canary were not significantly (*P* > 0.05) affected by lime or P rate (Table 4.6 and 4.7). However, the application of 120 kg S/ha of applied sulphur (gypsum) had a highly significant effect (*P* < 0.01) on the aluminium herbage concentration for both species.

4.4.7 Herbage zinc

Increased lime applications to the soil had a very highly significant ($P < 0.001$) effect on herbage zinc concentrations (Table 4.6). Zn concentrations decreased with increasing lime rate from 198.5 at 0 t lime/ha to 52.7 at 8 t lime/ha. Herbage Zn concentrations for hairy canary were very strongly ($P < 0.001$) influenced by lime application (Table 4.7) the maximum Zn concentration was observed at 0 t lime/ha at 112.8 mg/kg. This trend is highlighted in Figure 4.1 (b) which shows Zinc across both species decreased with an increase in pH which resulted from applied lime.

The application of 120 kg S/ha of applied sulphur (gypsum) increased ($P < 0.001$) the zinc herbage concentration for both species (Table 4.6 and 4.7).

Table 4.6 Herbage P, S, Mo, Mn, B, Al and Zn concentrations for tagasaste grown under glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) and increasing rates of P (four levels ranging from 0 – 500 mg P/kg soil).

	Shoot nutrient concentration (mg/kg)						
Tagasaste	[P]	[S]	[Mo]	[Mn]	[B]	[Al]	[Zn]
Lime rate (t/ha)							
0	200	129	0	367	15.8	113	199
2	183	119	0	207	19.0	108	187
4	214	159	0.01	99.9	17.8	89.3	81.2
8	199	151	0.04	48	14.1	88.9	52.7
SEM	19.6	90.2	0.08	18.4	1.01	12.4	16.9
LSD (5%)	39.8	18.3	0.05	37.2	2.05	25.2	34.2
Lime rate	ns	***	*	***	***	ns	***
P rate (mg/kg)							
0	169	152	0	154	16.5	98.2	111
50	188	133	0	167	16.5	103	102
150	189	147	0	160	16.2	100	116
500	262	142	0	176	18.4	89.7	151
SEM	12.6	11.6	0.01	56.7	1.26	13.6	32.1
LSD (5%)	25.6	23.5	0.02	115	2.55	27.6	65.2
P rate	***	ns	ns	ns	ns	ns	ns
Grand mean	202	144	0	164	16.9	97.7	120
SEM	32.2	20.6	0.09	75.1	2.27	26	49
LSD (5%)	65.4	41.8	0.07	152	4.6	52.8	83.2
Lime x P interaction	ns	ns	ns	ns	ns	ns	ns
ALL – L2P3	**	***	***	*	***	ns	***
L0P0 – L0P0-S	***	**	*	**	***	**	***
L0P0-S – L2P0-S	***	*	*	*	**	**	*

*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

Table 4.7 Herbage P, S, Mo, Mn, B, Al and Zn concentrations for hairy canary grown under glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) and increasing rates of P

*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

	Shoot nutrient concentration (mg/kg)						
Tagasaste	[P]	[S]	[Mo]	[Mn]	[B]	[Al]	[Zn]
Lime rate (t/ha)							
0	228	348	0	363	51.6	212	113
2	221	433	0	151	47	127	57.2
4	323	499	0.03	61.2	43	170	38.6
8	361	498	0.25	34.4	40.6	159	30.9
SEM	38.2	51.1	0.05	10.4	3.03	31.4	12.3
LSD (5%)	77.5	10.3	0.10	21.1	6.15	63.6	25.0
Lime rate	**	*	***	***	*	ns	***
P rate (mg/kg)							
0	2897	484	0.05	125	42.2	180	37.3
50	2607	438	0.06	134	44.0	152	46.0
150	3003	518	0.05	134	41.7	161	54.4
500	3129	389	0.02	144	52.2	177	84.9
SEM	46.7	55.2	0.07	57.9	3.02	34.5	17
LSD (5%)	94.6	11.1	0.15	117.5	6.13	69.9	34.5
P rate	**	ns	ns	ns	**	ns	*
Grand mean	291	455	0.05	134	45	168	55.6
SEM	84.9	10.6	0.12	68.3	6.05	65.9	29.3
LSD (5%)	17.2	21.5	0.25	138	12.2	133.5	59.5
Lime x P interaction	ns	ns	ns	ns	ns	ns	ns
ALL – L2P3	**	**	ns	***	***	**	**
L0P0 – L0P0-S	***	*	***	***	***	**	***
L0P0-S – L2P0-S	**	*	*	ns	***	**	**

(a)

(b)

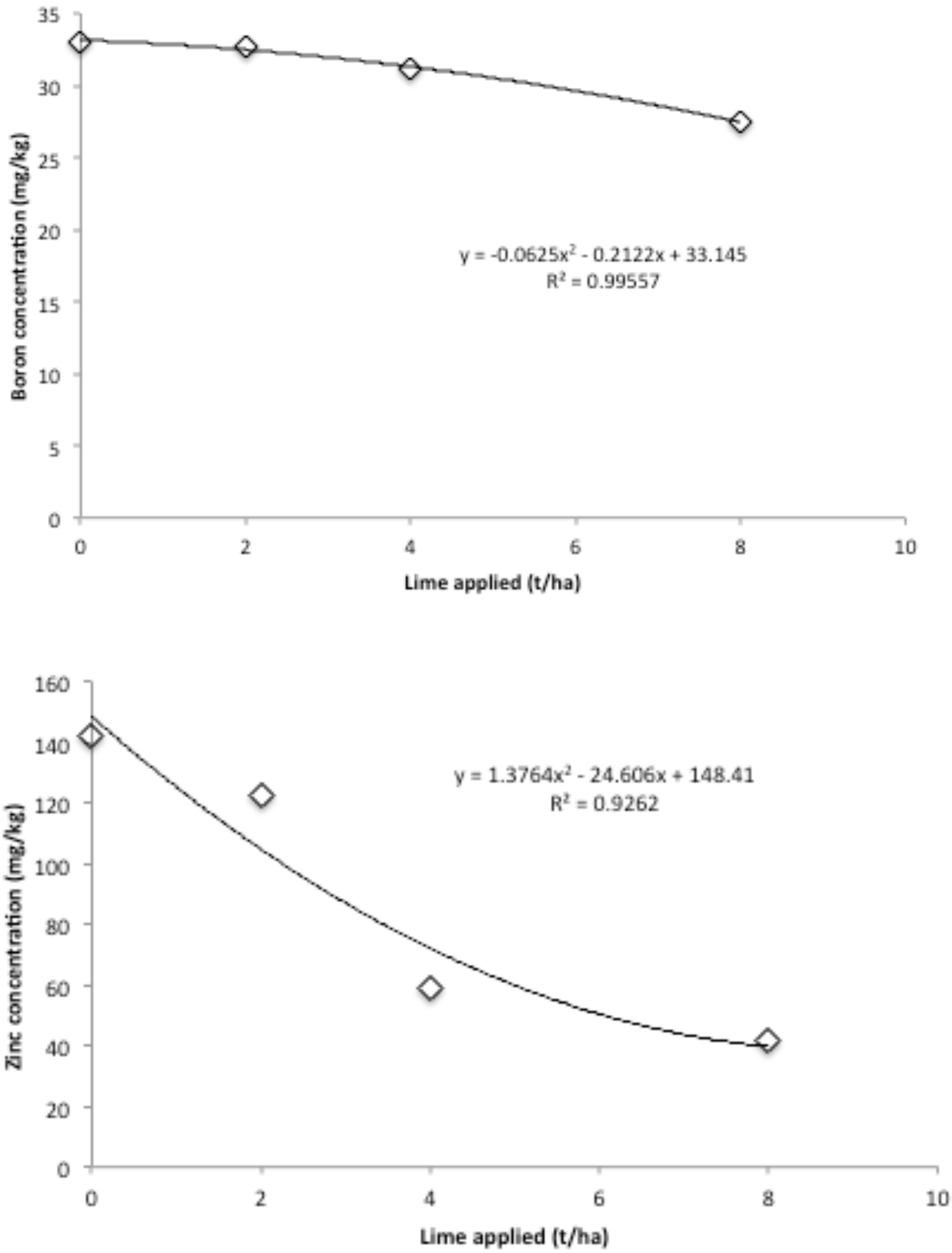


Figure 4.4 The relationship between concentrations of (a) Boron and (b) Zinc from the winter harvest across both species with increasing levels of lime (four levels ranging from 0 – 8 t lime/ha) grown under glasshouse conditions in a New Zealand high country soil.

4.5 Cocksfoot and legume mixture

Increasing lime rate had no significant affect ($P > 0.05$) on plant numbers or DM yields, except for the dry matter yield of cocksfoot which was significantly affected ($P < 0.05$) by lime rate. The maximum DM yields was observed at 4 t lime/ha of 3.81 g DM/pot (Figure 4). Any lime application above this decreased yields by the equivalent of 0.06 g DM/pot per t lime applied.

Lucerne plant numbers and DM yields were strongly increased by P rate ($P < 0.01$) (Table 4.8 and 4.9). The number of lucerene plants per pot increased from 0.33 plants/pot at 0 mg P/kg to 3.00 plants/pot at the high P treatment. Similarly, lucerne DM from yield increased 0.03 g DM/pot at 0 mg P/kg to 0.70 g DM/pot at the high P treatment. No other plant species were affected by the increasing application of lime rate ($P > 0.05$).

The application of 120 kg S/ha of applied sulphur (gypsum) had a very highly significant effect ($P < 0.001$) on the cocksfoot plant population and DM yield. Tagasaste and hairy canary DM yields were also affected significantly ($P < 0.05$) and highly significantly ($P < 0.01$) by the application of sulphur.

Table 4.8 Number of cocksfoot, tagasaste, hairy canary and lucerne plants under glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) and increasing rates of P (two levels 0 and 500 mg P/kg soil)

	Number of plants per pot			
Cocksfoot mixture	Cocksfoot	Tagasaste	Hairy Canary	Lucerne
Lime rate (t/ha)				
0	10.2	2.78	8.33	0.33
2	10.0	1.50	4.17	1.17
4	6.56	1.56	3.22	1.78
8	9.67	2.67	5.44	1.44
SEM	1.71	0.95	2.33	0.77
LSD (5%)	3.50	1.95	4.76	1.58
P value	ns	ns	ns	ns
P rate (mg/kg)				
0	9.08	1.58	5.50	0.33
500	9.28	2.56	5.61	1.44
SEM	2.19	1.14	2.98	0.83
LSD (5%)	4.49	2.33	6.08	1.70
P value	ns	ns	ns	**
Grand mean	9.03	2.18	5.39	1.18
SEM	2.90	2.09	5.31	1.6
LSD (5%)	7.99	4.28	10.84	3.28
Lime x P interaction	ns	ns	ns	ns
ALL – L2P3	***	**	*	**
L0P0 – L0P0-S	***	ns	ns	ns
L0P0-S – L2P0-S	**	**	*	**

*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

Table 4.9 Dry matter yield of cocksfoot, tagasaste, hairy canary and lucerne plants under glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

	Dry matter yield of individual species per pot (g DM)			
Cocksfoot mixture	Cocksfoot	Tagasaste	Hairy Canary	Lucerne
Lime rate (t/ha)				
0	2.56	0.40	0.31	0.03
2	3.64	0.15	0.08	0.10
4	3.81	0.40	0.11	0.29
8	3.56	0.44	0.14	0.07
SEM	0.55	0.25	0.11	0.17
LSD (5%)	1.12	0.51	0.23	0.34
P value	*	ns	ns	ns
P rate (mg/kg)				
0	3.08	0.21	0.21	0.03
500	3.36	0.37	0.16	0.09
SEM	0.66	0.28	0.14	0.17
LSD (5%)	1.35	0.59	0.29	0.34
P value	ns	ns	ns	**
Grand mean	3.37	0.36	0.16	0.12
SEM	2.90	2.09	5.31	1.60
LSD (5%)	7.99	4.28	10.84	3.28
Lime x P interaction	ns	ns	ns	ns
ALL – L2P3	***	**	ns	ns
L0P0 – L0P0-S	***	*	**	ns
L0P0-S – L2P0-S	***	ns	ns	ns

*** Significant at $P < 0.001$, ** significant at $P < 0.01$, significant at $P < 0.05$, ns – no significant difference.

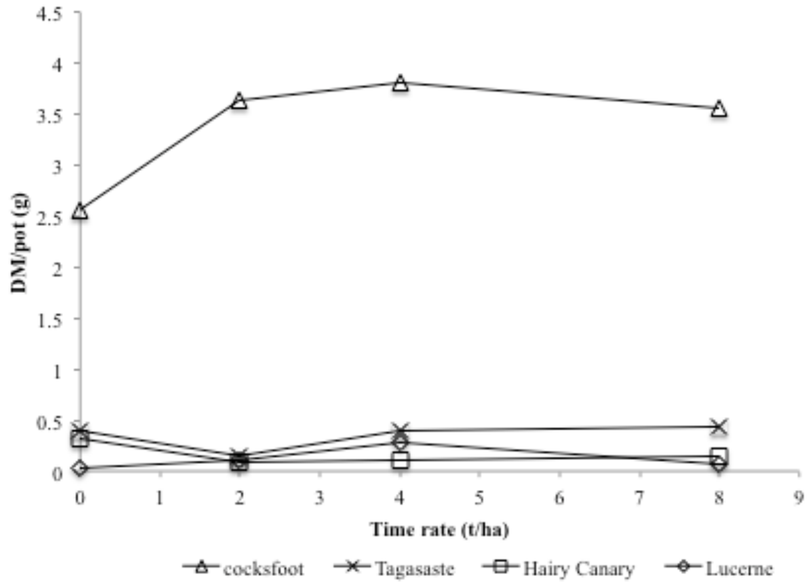


Figure 4.5 Total plant dry matter response to increasing levels of applied lime (four levels ranging from 0 – 8 t lime/ha) in a high country soil.

Cocksfoot plants significantly outcompeted the other three legume species (*P* > 0.001). The greatest plant numbers were observed for all species at 4 t lime/ha except for lucerne which plant number

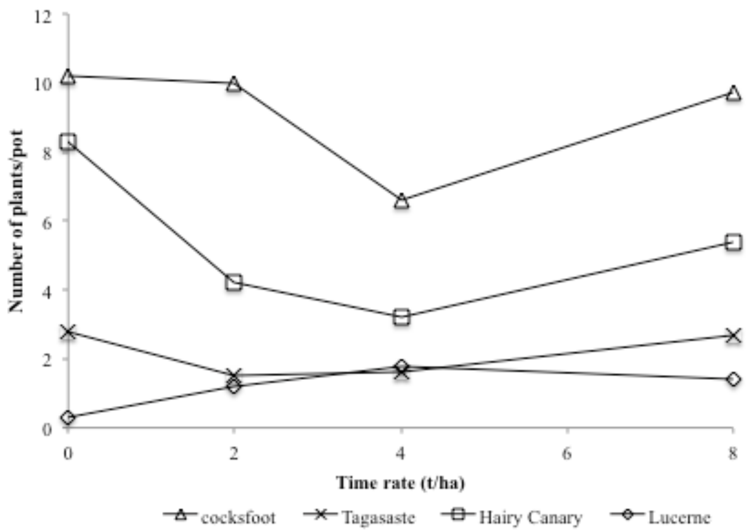


Figure 4.6 Total plant number response to increasing levels of applied lime (four levels ranging from 0 – 8 t lime/ha) in a high country soil.

4.6 Soil fertility and pH

4.6.1 Lime input effect on pH

As expected, the variable lime rates applied in this experiment significantly increased the pH of the soil (Figure 4.6) The pH increased from 4.4 at 0 t lime/ha to 6.5 at 8 t lime/ha. On average, to increase the soil pH by 0.1 units an application rate of 26 kg lime/ha would be needed.

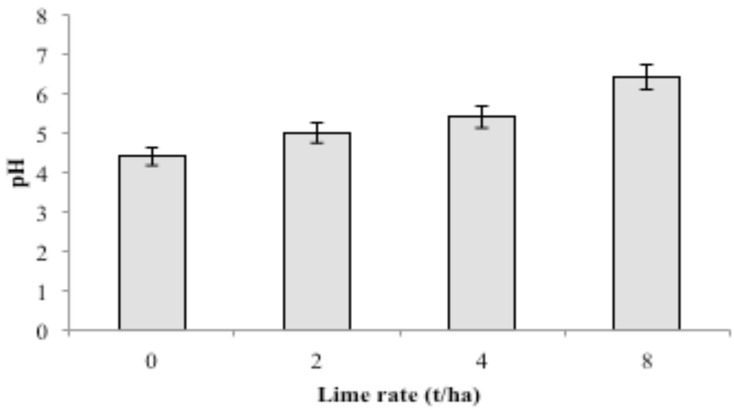


Figure 4.7 pH value of a New Zealand high country soil supplied with increasing levels of lime after the fifth legume herbage harvest. Values are means +/- SEM of pH values from pots across all pasture species within each lime treatment level (lime rate).

4.6.2 Phosphorus input effect on Olsen P

Increasing phosphorus input levels increased the soil Olsen P values (Figure 4.7). There was a linear increase in the Olsen P value from 17 µg/mL at 0 mg P/kg soil applied, to 134 µg/mL at 500 mg P/kg soil applied. An increase in Olsen P of 0.23 µg P/mL per mg P applied per kg soil.

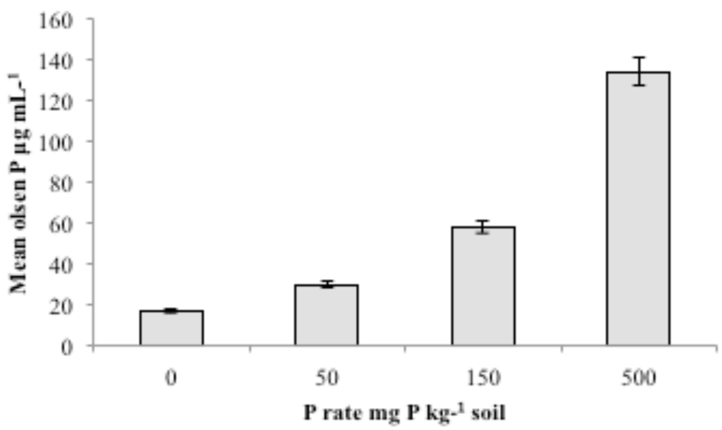


Figure 4.8 Olsen P µg/mL of a New Zealand high country soil supplied with increasing levels of Phosphorus after the fifth legume herbage harvest. Values are means +/- SEM of Olsen P values from pots across all pasture species within each P treatment level (P rate).

Chapter 5
Discussion

The objective of this experiment was to determine the growth response and nutrient uptake of two dryland legume species to different rates of lime, phosphorus and sulphur in an acidic high country soil during plant establishment. The key results and potential implications are discussed here.

5.1 Yield

5.1.1 Shoot yield

There was a highly significant difference in the shoot DM yield between tagasaste and hairy canary in this experiment. In terms of total DM, hairy canary yielded the highest 4.08 g DM/pot compared to 3.37 g DM/pot for tagasaste. This was due to the branching form of hairy canary in contrast to the single stem form of tagasaste. In the literature DM yield for tagasaste have been recorded at 13.1 g DM/pot (Jordan 2011). However, in that experiment multiple plants were harvested from a single height per harvest, increasing the accumulated dry matter yield in relation to this trial, which incorporated a maximum of six plants per pot. Douglas and Foote (1994) recorded yields equivalent to 2.5 g DM/pot for hairy canary, however this study occurred in the field. This may be useful in a practical sense in terms estimating yield reductions that occur in an uncontrolled field environment. The high yields of the two species in this experiment were expected as a large portion of this study occurred in a glasshouse where grazing did not occur and soil moisture was not low. Under grazed field conditions, tagasaste yield is significantly affected by the distance between tree plantings and the age of trees (Townsend & Radcliffe 1990).

A highly significant ($P < 0.001$) interaction between species and lime rate was found, which indicates that the two species responded to lime in different ways. This was to be expected each species exhibited a different pH range at which maximum growth was achieved in this experiment. Tagasaste was the most tolerant of the two species to very low soil pH and observed only a 39% reduction in yield from 3.26 g DM/pot at the optimum 4 t lime/ha to 2.32 g DM/pot at 0 t lime/ha. In contrast, hairy canary observed 42% reduction in yield at the lower soil pH. This result supports and expands upon that of Willis *et al.* (1989), who indicated that hairy canary prefers a soil pH above 5.4 but did not include tagasaste in his experiment. Regardless, maximum yields for the two species occurred at 4 t lime/ha (soil pH of 5.4). The increase in yield was likely to be driven by the increasing P and Mo availability resulting from increased soil pH and amelioration of Al toxicity. A combination of these factors, acting individually or collectively, would be expected to result in a positive yield response to lime up to a soil pH of 5.4. The species by phosphorus interaction was not significant indicating that both species responded similarly to any P additions.

There was no significant difference in the autumn, winter or total shoot yield response to phosphorous application between the two species in this experiment. This is in contrast to the results obtained from Jordan (2011) who observed a very significant affect ($P < 0.001$) on the growth of tagasaste in response to increasing P rates. Interestingly, in the same study tagasaste was the highest yielding out of 12 annual and perennial species when no P was applied. The P rate at which maximum yield was achieved was the lowest for tagasaste, 132 mg P kg^{-1} compared to 669 mg P kg^{-1} for other legume species (Jordan, 2011), indicating the ability of tagasaste to grow in low fertility soils. Hairy canary was not included in Jordan (2011) experiment and response similarities between the two species is not documented in the scarce literature that is available.

This result therefore provides valuable new information for high country farmers seeking solutions for low fertility situations. However, it is evident that the establishment phase is critical for the long term survival of these legumes. Light grazing is recommended during the first year and sowing is likely to occur in strips on areas of farms exposed to climatic extremes and low soil fertility conditions (Willis *et al.* 1989). Further field investigations should be conducted to better understand both tagasaste and hairy canary response to increasing lime and phosphorus inputs on acidic high country soils, as well as to look into the mechanisms driving differences in yield response.

5.1.2 Root yield

Lime addition significantly increased ($P < 0.05$) the mean root yield of both legume species. At the most acidic soil pH (pH 4.9) hairy canary was the most productive legume species with a maximum root DM yield of 0.78 g DM/pot, producing 105% greater root mass than tagasaste. The tolerance of these alternative legumes to acidic soils is evident as the greatest root dry matter response occurred at a pH of 5.0 - 5.5 (lime rate 2 – 4 t ha^{-1}). At the highest lime rate of 8 t lime/ha both species showed a significant reduction in root yield.

There was no significant root yield response to phosphorus application for tagasaste or hairy canary. There is currently no literature on the root yield response of these two legumes in relation to increasing lime and phosphorus rates, therefore this present’s new information.

5.2 Physical measurements

5.2.1 Shoot length

Tagasaste was the most responsive legume to phosphorus inputs above the control (0mg P kg^{-1}), with a 21% increase in total shoot length when 50 mg P kg^{-1} was applied, compared with hairy canary which increased by 11% when 50 mg P kg^{-1} was applied. At increased P rates shoot length decreased, suggesting that factors other than soil P availability were limiting establishment growth. Increasing lime applications had no significant effect on tagasaste shoot length. In contrast, hairy canary's showed a positive shoot length response ($P < 0.01$) up to a lime application rate of 4 t ha^{-1}. Beyond this level a depression in available phosphorus and boron likely reduced shoot lengths. There has been no research on the effects of increasing lime and phosphorus rates on the shoot length of tagasaste and hairy canary. Further field investigations should be conducted to better understand both tagasaste and hairy canary response to increasing lime and phosphorus inputs on acidic high country soils, in addition to elucidating the mechanisms driving these responses.

5.2.2. Root length

Autumn root length for tagasaste and hairy canary was significantly ($P < 0.05$) increased by the application of lime. Interestingly, a very similar response to lime was observed for shoot and root length. The greatest length response was observed at 2 t lime/ha, followed by a 13% reduction in length at the application rate of 8 t lime/ha for hairy canary. No response was observed for the two species when increasing rates of P were applied. However, these results may not be indicative of root growth in the field as each plant was physically restricted to a maximum root length due to the depth of the 5 L pots used. The depth of soil was 170 mm, however some roots exceeded this length due to variable horizontal growth patterns. To date, no literature has reported root growth of hairy canary and tagasaste in acidic high country soils.

5.3 Nodulation

The nodulation of tagasaste and hairy canary was examined and scored on a basis of the number of pink pigmented nodules present on the roots. Increasing lime rate resulted in a significant ($P < 0.05$) response for tagasaste for autumn and winter harvests. The number of pigmented nodules was higher for higher soil pH's with a peak score at 8 t lime/ha and 2 t lime/ha for the autumn and winter harvests, respectively. The fluctuation in these results suggests that rhizobia specific to tagasaste may have an increased tolerance to a wide range of soil pH's. This result supports that of Townsend and Radcliffe (1990) and Jordan (2011), where significant tagasaste growth occurred in soils with a pH below 5.5 and in soils with low levels of available phosphorus, nitrogen and molybdenum which are evident in high pH soils.

The ability of tagasaste to form root nodules in the presence of over 20 different strains of rhizobia (Gault *et al.* 1994) also increases the chance of successful nodulation occurring. Hairy canary had no nodulation response to increasing lime or phosphorus rates. Interestingly, Wills *et al.* (2003) indicated that inoculation failure is not a major problem for hairy canary, thus soil fertility may not have an effect on nodulation. As such, this information collectively suggests that both tagasaste and hairy canary are species well suited to nodulate in acidic high country soils.

There were still some pigmented nodules with no lime application for both species, which indicates that species could actively fix N in an acidic environment (pH 4.9). This is inconsistent with findings from Willis *et al.* (1989) which indicated that hairy canary prefers soils with a pH range of 5.4 – 8.6. A low nodule score indicated less pigmented nodules, however, the non-pigmented nodules could have been fixing N, however this analysis was beyond the scope of this study. There has been no investigation into the capacity of N fixation by hairy canary or tagasaste, therefore this is new and valuable information on these species.

Practical application of these legumes in the field is likely to be in a harsh climatic high country environment where soil fertility is low. Once established, these species may provide significant nitrogen fixation where other legume species have been unsuccessful due to soil acidity. This annual N input would be a substantial step forward to lift soil fertility for other pasture species. From this research it is clear that the establishment period is crucial for both legumes and thus it is recommended grazing be limited to one light graze in the first year. Multiple grazing's may be possible with mature plants however, this is not illustrated in the literature and further work is required in this area.

5.4 Herbage nutrient concentrations

5.4.1 Phosphorus

The uptake of phosphorus by plants is driven by the availability of P in the soil. As to be expected, an increased rate of P application from 0 to 500 mg kg^{-1} increased the availability of P in the soil, resulting in greater P uptake from plants and significantly (P <0.01) increasing the P concentration in the plant shoot tissue. Both species achieved maximum shoot P levels with the maximum rate of applied P (500 mg P/kg), which resulted in an Olsen P of 134 μg/mL.

Phosphorus at the highest application significantly ($P < 0.01$) increases the shoot length of tagasaste plants for the winter harvests (Table 4.6 and 4.7).

Tagasaste and hairy canary showed no ($P > 0.05$) differences in yield across P rates and demonstrated the ability to grow consistently at a range of P fertility levels. Different yield responses to P between species and at different P concentrations in the herbage are common (Syers *et al.* 2008). This is likely to be a result of the different physiological requirements of each species and their adaptations to live in low P environments. The mean Olsen P levels (17 µg/mL) at the commencement of the experiment, is consistent to levels found on many high country farms. There was no response to added P at higher rates, suggesting soil P levels were at the optimum for tagasaste and hairy canary for the duration of the experiment.

Increasing lime rate significantly ($P < 0.01$) increased the herbage P concentrations of hairy canary. It would be expected that initially phosphate becomes more available as lime rate increases above 0 t ha^{-1} due to the reduction of P binding by Al. Hydrated Al oxides are dominant phosphate absorbing surfaces (Haynes 1982). In contrast, a reduction in shoot P concentration at higher lime application rates (> 4 t lime/ha) was observed for tagasaste. The contrasting result between these two legume species is interesting and suggests differing P uptake mechanisms may be occurring. This result requires further confirmation and investigation in future research.

5.4.2 Sulphur

The shoot sulphur concentration reflected the uptake of S by the plants and for both species the S concentration was significantly affected ($P < 0.01$) by lime rate. There was a steady increase in herbage S with increased lime rate up to a certain point, which was species dependant. For both species the concentrations peaked at 4 t lime/ha (144 and 456 mg/kg for tagasaste and hairy canary, respectively), which was higher than the optimum level for hill and high country herbage S concentration identified at 0.18 – 0.22% S (Craighead & Metherell 2006), which represents a shoot S concentration for tagasaste and hairy canary at the equivalent lime rate of 4 t/ha^{-1}, 219 µg mL. However, the soil used in this experiment exceeded this level due to high levels of base fertiliser. In this experiment it appeared that shoot S concentrations were the highest at the at the treatment level where yields and shoot lengths were highest, which represents the lime rate at which the plant performed the best in terms of yield and nutrient uptake.

5.4.3 Molybdenum

Molybdenum is an essential plant micro nutrient, particularly for legume species because of the key role it plays as an electron carrier during N fixation (F.A.O 1993) and thus the successful addition of N to the soil/plant system. The application of lime showed a significant ($P < 0.05$) increase in herbage Mo concentration of both species as soil pH level rose in response to lime inputs. The concentration of Mo in the plant herbage followed an increase up to 8 t lime/ha which is supported by Goldburg *et al.* (1996) who reported an increase in the availability of Mo with lime applications. At a pH greater than 5.5 levels of exchangeable Al and Fe, which adsorbs Mo, are reduced, thus increasing Mo availability.

One of the key dry matter responses to lime has been associated with an increased concentration of shoot Mo. New Zealand soils have typically been limed to increase the availability of Mo for legumes as it is important in the N fixing process (McClaren & Cameron 1996). The soil examined in this experiment was very acidic (pH 4.9) and high in exchangeable Al (> 10 mg kg^{-1}) which indicates why no Mo was detected in herbage below a lime rate of 4 t/ha^{-1}. However, zero Mo in herbage is an unusual result and strongly indicates that this soil type is also very low in plant available Mo. As lime rates increased, plant Mo concentrations increased dramatically for hairy canary ($P < 0.001$). It is hypothesised that tagasaste has a different optimum herbage Mo concentration as it continued to yield well under very low Mo concentrations (0.01 mg/kg). There is currently no literature on the optimum Mo concentrations for these two legumes, therefore this represents new and valuable information.

Neither of the species examined in this trial had a shoot Mo response to increasing phosphorus inputs which may be due to the medium-high levels of soil available P which generally increases Mo availability (Ribera *et al.* 2010).

5.4.4 Manganese

Both of the species examined in this trial showed a highly significant ($P < 0.001$) decrease in the shoot manganese concentration as a result of increasing lime inputs, which indicates that Mn availability decreases with increasing pH. This may partly explain the increase in yield with lime application due to the reduced Mn toxicity which occurs in acidic soils (McClaren & Cameron 1996). Mn is highly toxic generally, phosphorus inputs did not affect the Mn concentration of plant shoots. The effect of Mn on tagasaste and hairy canary is not existent in the literature and more research needs to be carried out to determine the effects of Mn on the productivity of these two legumes.

5.4.5 Boron

The concentrations of boron in the herbage were significantly decreased ($P < 0.05$) by increasing lime rate for tagasaste and hairy canary (Table 4.6 and 4.7). Boron availability decreases with increasing pH (McClaren & Cameron 1996). Shoot B concentration is considered to be high in legumes when levels are between 50 – 100 mg B kg^{-1}, with toxicity occurring at plant concentrations above these levels (Clark & Baligar 2003). The concentration of shoot B in this experiment did not exceed these levels, therefore B did not reach toxic levels in the plants

There has been no research investigating the effect of shoot B concentrations of tagasaste and hairy canary. However, from this experiment it is apparent that greater lime inputs reduced shoot B concentrations. It is unknown at what concentration B became deficient, although a reduction in yield was observed at the highest lime input which correlated to the lowest shoot B concentration.

5.4.6 Aluminium

The quantity of soil aluminium in plant available form and therefore the potential for toxicity are strongly influenced by soil pH. Neither tagasaste nor hairy canary Al shoot concentrations were affected by increasing lime or phosphorus rates (Table 4.6 and 4.7). This result was expected, as soil exchangeable Al concentrations often have no correlation with plant shoot Al concentrations (Moir and Moot, 2010). At a soil concentration of 3 mg Al/kg and above toxicity symptoms in pasture legumes are observed (Moir, 2013). The original concentration of aluminium in the acidic Armidale soil was very high (15.5 mg/kg) and was therefore at toxic levels at the original soil pH of 4.9. Highest herbage Al concentrations were found in plants where the original soil with zero lime applied at the lowest lime treatment, and declined with further lime applied as a result of reduced acidity. Calcium displaces Al from exchange sites with applied lime and reduces the availability of Al for plant uptake.

The concentration of the Al at which toxicity occurs depends on the tolerance of the plant species. There has been no research investigating the effects of lime on shoot Al concentrations of hairy canary and tagasaste.

5.4.7 Zinc

Herbage Zn concentrations decreased significantly ($P < 0.001$) with increasing lime rates. Zn concentration decreased with increasing lime rates as a result of increasing pH, which increases legume susceptibility to Zn deficiency. Deficiency is primarily due to changes in the chemical nature of the soil. Zn is an essential part of over 300 enzymes in plants and Mengel and Kirkby (2001) identified the critical level for legumes as 15 $\mu g\ g^{-1}$. Thus, the two legumes in this study may have been deficient at the high lime rate treatment, however a critical value for tagasaste and hairy canary is not documented in current literature for comparison.

5.5 Cocksfoot and legume mixture

The addition of lime had no effect on the number of plants per pot for all four species. Phosphorus supply had a similar affect, with a significant ($P < 0.01$) response only observed with lucerne. For lucerne, the number of plants/pot was highest at the highest P rate. This data from this analysis is seen as a direct comparison between the numbers of plants grown per species expressed in Figure 4.6. Cocksfoot produced 365% more plants than tagasaste and 26% more plants than hairy canary. However, it is important to note that this correlation in plant number does not correspond to dry matter yield (Figure 4.5). Cocksfoot was the only species to respond significantly ($P < 0.05$) to increasing lime rate in terms of DM yield.

The purpose of the cocksfoot mixture was to determine how tagasaste and hairy canary would establish and grow in a competitive environment during establishment. Tagasaste in particular was vastly outcompeted by the grass species during establishment and although hairy canary produced a greater proportion of plants in relation to tagasaste, it was significantly out yielded ($P < 0.01$). Thus, recommendations when using these new legume species are; to avoid competition at establishment by spraying competing grass species with herbicide before sowing, planting the legume species early, allow them to successfully establish and then sow companion species. Sowing is unlikely to be suitable for entire paddocks, however, these legume could be of considerable value on very tough and acidic high country blocks where current production is virtually nil. Field experiments are required to evaluate and determine 'best practice' for sowing and grazing of tagasaste and hairy canary in the field.

Chapter 6
Conclusions

The objective of this study was to determine the growth response, yield and nutrient uptake response of two legumes on an acidic high country soil from Central Otago. Treatment effects were identified in a pot trial under a combination of glasshouse and controlled external conditions at Lincoln University.

Two novel woody perennial legumes were investigated; tagasaste and hairy canary. The highest yielding species was hairy canary with a grand mean of 3.77 g DM pot^{-1}. Lime inputs significantly ($P < 0.01$) increased the yields of both species up to a maximum point which was species specific, at which point yields declined with further lime additions. The lime rate and subsequent pH value, at which plants achieved maximum yield varied between 2 – 4 t lime/ha, representing a soil pH of 5.0 – 5.4. This was driven by a substantial decrease in soil exchangeable Al levels and greater P and Mo availability. At a lime application rate of 8 t lime/ha yield of the legumes was reduced, probably as a result of decreased P and B availability. Tagasaste was the most tolerant species to severe acidic soil conditions (pH 4.4 – 5.0).

Phosphorus inputs failed ($P > 0.05$) to increase the DM yield of both legume species. However, both species were found to be efficient at utilising low levels of P, yielding well over all four phosphorus treatment rates. The Olsen P of the soil at the commencement of this experiment was already at a medium level (Olsen P = 24 µg mL^{-1}), explaining why the plant yield response to increasing P inputs was not significant. This also explains why there was no significant interaction between lime and phosphorus treatments, as increasing lime inputs would typically reduce phosphorus availability.

Trace elements had an effect on yields as shoot Boron concentrations reduced with increasing soil pH, while Molybdenum concentrations increased as a result of higher lime rates. Shoot aluminium concentrations were highest at low soil pH, which increased the likelihood of aluminium toxicity reducing plant growth.

Tagasaste and hairy canary in the field are often outcompeted at establishment by aggressive species. The pasture mixture experiment identified interspecies competition at establishment in terms of persistence of hairy canary and tagasaste. The impact of growing in combination with other species at establishment significantly ($P < 0.01$) reduced the yield of the two species which has implications for the field as tagasaste and hairy canary may be the main nitrogen source in harsh high country environments.

Suggestions for further research:

- The results from these findings need to be confirmed in the field, under natural climatic (rainfall, temperature, wind), topographical (aspect and altitude) and grazing (stock preference, palatability and grazing tolerance) conditions, and the ability of each species to successfully establish and persist long term in the harsh high country environment.
- This experiment has been carried out on a specific soil with medium P availability. The growth of these legumes should be carried out on a range of hill and high country soil types in New Zealand to determine if the yield response to nutrients, herbage concentrations and nodulation follow similar trends to those found in this study.
- Performing an analysis for herbage nitrogen and identifying rhizobia present within the root nodules would provide valuable information. Determining the activity of nodules, particularly non-pigmented nodules, using Acetylene reduction tests to confirm if the nodule is undergoing nitrogen fixation.
- Trace element effects on these legume species should be investigated further to separate the effects of P deficiency and trace element deficiency or toxicity on plant growth.

References

Allan, B.E. 1985. Grazing effects on pasture and animal production from oversown tussock grassland. *Proceedings of the New Zealand Grassland Association 46*: 119-125.

Barrow, N.J. 1975. The response to phosphate fertiliser of two annual pasture species. I. Effect on the soil's ability to adsorb phosphate on comparitive phosphate requirement. *Australian Journal of Agricultural Research 26*: 137-143.

Batten, G.J. 1985. Observations of fodder trees, and research needs. pp. 14-28. *In*: Fodder trees: a summary of current research in New Zealand Eds. Logan, L.A.; Radcliffe, J.E. New Zealand Department of Scientific and Industrial Research. Crop Research Division, Chrsitchurch, New Zealand.

Bell, L.W.; Moore, G.A.; Ewing, M.A.; Bennett, S.J. 2005. Establishment and summer survival of the perennial legumes *Dorycnium hirsutum* and *D. rectum* in Mediterranean environments. *Australian Journal of Experimental Agriculture 45*: 1245-1254.

Blackmore, L.C.; Searle, P.L.; Daly, B.K. 1972. Methods for chemical analysis of soils. Scientiifc Report, New Zealand Soil Bureau.

Blackmore, L.C.; Searle, P.L.; Daly, B.K. 1987. Methods for chemical analysis of soils. Scientific Report, New Zealand Soil Bureau.

Bolan, N.S.; Hedley, M.J. 2003. Role of carbon, nitrogen and sulphur cycles in soil acidification. *Handbook of Soil Acidity*: 29-56.

Borens, F. 1986 The nutritive feeding value of tagasaste (*Chamaecytisus palmensis)*. Lincoln College, Canterbury, New Zealand

Borens, F.M.P.; Poppi, D.P. 1990. The nutritive value for ruminants of tagasaste (*Chamaecytisus palmensis*), a leguminous tree. *Animal feed Science and Technology 28*: 275-292.

Clark, R.B.; Baligar, V.C. 2003. Mineral concentrations of forage legumes and grasses grown in acidic soil amended with flue gas desulfurization products. *Communications in Soil and Plant Analysis 34*: 1681-1707.

Correa, O.S.; Aranda, A.; Barneix, A.J. 2001. Effects of pH on growth nodulation of two forage legumes. *Journal of Plant Nutrition 24*: 1367-1375.

Costello, T.; Costello, A. 2003. Subterranean Clover in North Canterbury sheep pastures. pp. 189-192. *In*: Legumes for Dryland Pastures. Ed. Moot, D.J. New Zealand Grassland Association, Wellington.

Craighead, M.D. 2005. The effect of two lime sources on short-term changes in soil pH under Marlborough hill country pasture. *Proceedings of the New Zealand Grassland Association 67*: 155-162.

Craighead, M.D.; Metherell, A.K. 2006. The impact of the form and frequency of sulphur on pasture yield and composition in South Island high country. *Proceedings of the New Zealand Grassland Association 68*: 361-367.

Douglas, G.B.; Foote, A.G. 1994. Establishment of perennial species useful for soil conservation and as forages. *New Zealand Journal of Agricultural Research 37*: 1-9.

Edmeades, D.C.; Smart, C.E.; Wheeler, D.M. 1983. Aluminium toxicity in New Zealand Soils: preliminary results on the development of diagnostic criteria. *New Zealand Journal of Agricultural Research 38*: 21-32.

F.A.O 1993. Technicl handbook on Symbiotic Nitrogen Fixation - Legume and Rhizobium Food and Agriculture Organization of the United Nations, Rome.

Gault, R.R.; Pilka, A.; Hebb, D.M.; Brockwell, J. 1994. Nodulation studies on legumes exotic to Australia: symbiotic relationships between *Chamaecytisus palmensis* (tagasaste) and *Lotus* spp. *Australian Journal of Experimental Agriculture 34*: 385-394.

Goldburg, S.; Forster, H.S.; Godfrey, C.L. 1996. Molybdenum adsorption on oxides, clay mineralys, and soils. *Soil Science Society of America 60* 425-432.

Gupta, U.C. 1997. Molybdenum in agriculture. Cambridge University Press, Cambridge, England.

Haynes, R.J. 1982. Effects of liming on phosphate availability in acid soils - A critical review. *Plant and Soil 68*: 289-308.

Hesse, P.R. 1971. A textbook of soil chemical analysis. Chemical Pub. Co. 1972, Michigan.

Horneck, D.A.; Miller, R.O. 1998. Determination of total nitroegen in plant tissue. pp. 75-83. *In*: Handbook of reference methods for plant analysis. Ed. Kaira, Y.P. CRC Press, New York.

Jordan, P.R. 2011 Response of 12 pasture legumes to phosphorus and lime additions when growin in a high country soil under glasshouse conditions Lincoln University, Christchurch, New Zealand

Keeney, D.R.; Bremner, J.M. 1966. Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agronomy Journal 58*.

Kemp, P.D.; Condron, L.M.; Matthew, C. 1999. Pastures and soil fertility. pp. 67-83. *In*: New Zealand Pasture and Crop Science. Eds. White, J.; Hodgson, J. Oxford University Press, Auckland, New Zealand.

Lambert, M.G.; Clark, D.A.; Costall, D.A.; Budding, P.J. 1988. Phosphorus and sulphur accumulation after long-term superphosphate application to grazed hill country. pp. 95-100. *In*: Towards the more efficient use of soil and fertiliser sulphur. Eds. White, R.E.; Currie, L.D. Massey University, Massey University, Palmerston North.

Lambert, M.G.; Clark, D.A.; Grant, D.A.; Costall, D.A. 1986. Influence of fertiliser and grazing management on North Island moist hill country. *New Zealand Journal of Agricultural Research 29*: 1-10.

Maxwell, T.M.R.; Moir, J.L.; Edwards, G.R. 2012. Sulphur and lime response of four adventive annual clovers grown in a New Zealand high coutry soil under glasshouse conditions. *New Zealand Journal of Agricultural Research 55*: 47-62.

McClaren, R.G.; Cameron, K.C. 1996. Soil Science. Sustainable production and enviromental protection. Oxford University Press, Melbourne.

Mengel, K.; Kirkby, E.A. 2001. Principals of plant nutrition. 5th edn. Kluwer Academic Publisher, Dordrecht, Netherlands.

Metson, A.J. 1968. The long term potassium-supplying power of New Zealand soils. *Trans 9th International Congress in Soil Science 2*: 621-629.

Metson, A.J. 1975. Magnesium in New Zealand soil II. *New Zealand Journal of Agricultural Research 18*.

Metson, A.J.; Arbuckle, R.H.; Saunders, M.L. 1956. The potassium-supplying power of New Zealand soils as determind by a modified normal-nitroc acid method. *Trans 6th International Congress in Soil Science B*: 619-627.

Moir, J.L. 2013. Why is Aluminium a challenge? New Zealand Merino Company Field Day: Lupins, Lincoln University.

Moir, J.L.; Hedley, M.J.; Mackay, A.D.; Tillman, R.W. 1997. The effect of fertiliser history on nutrient accumulation and plant-available nutrient supply in legume-based pasture soils. pp. 68-69. *In*: XVII International Grassland Congress. Eds. Buchanan-Smith, J.G.; Bailey, L.D.; McCaughey, P., Winnipeg, Canada.

Moir, J.L.; Moot, D.J. 2010. Soil pH, exchangeable aluminium and lucerne yield responses to lime in a South Island high country soil. *Proceedings of the New Zealand Grassland Association 72*: 191-196.

Moir, J.L.; Schotter, D.R.; Hedley, M.J.; Mackay, A.D. 2000. A climate-driven, soil fertility dependant, pasture production model. *New Zealand Journal of Agricultural Research 43*: 491-500.

Morton, J.D.; Roberts, A.H.C. 1999. Fertiliser use on New Zealand sheep and beef farms. *The New Zealand Fertiliser Manufacturers' Association*: 1-48.

O'Connor, K.F. 1969. Studies of lime and phosphate relations of rhizobia-legume systems. *Soil News 5*: 154-167.

Olsen, S.R.; Cole, C.V.; Watanabe, F.S. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *United States Department of Agriculture 939*.

Peoples, M.B.; Faizah, A.W.; Rerkasem, B.; Herridge, D.F. 1989. Methods for evaluating nitrogen fixation by nodulated legumes in the field, *Momograph No 11*. Australian Centre for International Agricultural Research No., Canberra. 12-13 pp.

Radcliffe, J.E. 1983. Fodder trees - an opinion for dry hill country. *In*: Proceedings of the 1983 Hill and High Country Seminar. Special Publication 26. Ed. Robertson, B.T. Centre for Resource Management, Lincoln College, Canterbury, New Zealand.

Raven, P.H.; Evert, R.F.; Eichhorn, S.E. 1992. Biology of Plants. 5th Edition. . Worth Publishers, New York.

Ribera, A.E.; Mora, M.D.; Ghiselini, V.; Demanet, R.; Gallardo, F. 2010. Phosphorus-molybdenum relationship in the soil and red clover (*Trifolium pratense* L.) on an acid andisol. *Journal of Soil Science and Plant Nutrition 10*: 78-91.

Rickard, D.S.; McBride, S.D. 1986. Irrigated and non irrigated pasture production at Winchmore 1960-1985. *Technical Report 21 Winchmore Irrigation and Research Station, Ministry of Agriculture and Fisheries, New Zealand*.

Russell, A.C. 1985. Effect of nitrogen, phosphate, lime and inoculm on establishment of tagasaste (pot trial). pp. 34-45. *In*: Fodder Trees: a summary of current research in New Zealand. Eds. Logan, L.A.; Radcliffe, J.E. New Zealand Department of Scientific and Industrial Research. Crop Research Division, New Zealand.

Sanyal, S.K.; Datta, S.K.d. 1991. Chemistry of phosphorous transformations in soil. *Advances in Soil Science 16*: 1-20.

Saunders, W.M.H. 1965. Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter and other soil properties. *New Zealand Journal of Agricultural Research 8*.

Schollenberger, C.J.; Simon, R.H. 1945. Determination of exchange capacity and exchangeable bases in soil - ammonium acetate method. *Soil Science 59*: 13-24.

Scott, D. 2003. Dryland legumes: perspectives and problems. pp. 27-36. *In*: Legumes for Dryland Pastures. Ed. Moot, D.J. Lincoln University, Christchurch, New Zealand.

Scott, D.; Maunsell, L.A.; Keoghan, J.M.; Allan, B.E.; Lowther, W.L.; Cossens, G.G. 1995. A guide to pastures and pasture species for the New Zealand high country. *In*: Grassland Research and Practice Series. Eds. Round-Turner, N.; Ryde, D. New Zealand Grasslands Association Incorporated, Palmerston North, New Zealand.

Searle, P.L. 1979. Measurement of adsorbed sulphate in soils - effects of varying soil - extractant ratios and methods of measurement. *New Zealand Journal of Agricultural Research 22*: 287-290.

Sherrell, C.G.; Metherell, A.K. 1986. Diagnosis and treatment of molybdenum deficiency in pastures. *Proceedings of the New Zealand Grassland Association 47*: 203-209.

Snook, L.C. 1982. Tagasaste (tree lucerne): a shrub with high potential as a productive fodder crop. *Journal of the Australian Institute of Agricultural Science 48*: 209-214.

Syers, J.K.; Johnstone, A.E.; Curtin, D. 2008. Efficiency of soil and fertiliser phosphorous use. *Fertiliser and Plant Nutrition Bulletin*: 1-11.

Townsend, R.J.; Radcliffe, J.E. 1987. Establishment and management of tagasaste. *Proceedings of the New Zealand Grasslands Association 48*: 109-113.

Townsend, R.J.; Radcliffe, J.E. 1990. Tagasaste forage production systems. *New Zealand Journal of Agricultural Research 33*: 627-634.

Voon, C.C. 1986. Establishment of tagasaste (Chamencytisus palmensis). *A thesis submitted in paritial fulfilment for the degree Master of Agricultural Science In Lincoln University, New Zealand*: 15-27.

Waring, S.A.; Bremner, J.M. 1964. Ammonium production in soil under waterlogged conditions as an index of nirtogen availability. *Nature 201*: 951.

Wheeler, D.M.; O'Connor, M.B. 1998. Why do pastures respond to lime? *Proceedings of the New Zealand Grassland Association 28*: 105-112.

White, J.; Hodgson, J. 1999. New Zealand Pasture and Crop Science. Oxford University Press, Melbourne.

Willis, B., J; Begg, J.S.C.; Foote, A.G. 1989. *Dorycnium* species - Two legumes with potential for dryland pasture rejuvenation and resource conservation in New Zealand. *Proceedings of the New Zealand Grasslands Association 50*: 169-174.

Wills, B.; Trainor, K.; Scott, D. 2003. Legumes for South Island tussock grassland environments - an evaluation of plant survivial and growth at some inland Otago and Canterbury trials. pp. 131-142. *In*: Legumes for Dryland Pastures. Ed. Moot, D.J. Lincoln University, Canterbury, New Zealand.

Woodman, R.F.; Keoghan, J.M.; Allan, B.E. 1992. Pature species for drought-prone lower slopes in South Island high country. *Proceedings of the New Zealand Grasslands Association 54*: 115-120.

Appendices

A 1 Full harvest data

A 1.1 Tagasaste shoot length across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
T	L0P0-S	23	52	71	250	295	T	L2P2	39	62	184	440	431
T	L0P0-S	24	60	129	350	370	T	L2P2	71	72	193	330	600
T	L0P0-S	52	80	155	560	552	T	L2P2	45	53	56	330	472
T	L0P0-S	28	40	166	360	448	T	L2P2	47	75	104	440	511
T	L0P0	31	54	60	240	343	T	L2P3	38	52	92	330	625
T	L0P0	28	35	65	300	425	T	L2P3	41	65	94	480	362
T	L0P0	34	70	183	420	413	T	L2P3	52	75	200	340	543
T	L0P0	27	45	69	250	344	T	L2P3	45	40	122	260	520
T	L0P1	39	64	110	430	291	T	L3P0	72	51	88	300	553
T	L0P1	37	70	154	330	346	T	L3P0	61	65	136	270	635
T	L0P1	49	80	152	300	414	T	L3P0	44	49	71	230	499
T	L0P1	34	66	164	270	241	T	L3P0	45	52	72	240	457
T	L0P2	42	76	265	590	480	T	L3P1	61	49	126	290	563
T	L0P2	33	90	154	540	483	T	L3P1	44	45	102	250	527
T	L0P2	33	54	59	300	408	T	L3P1	35	51	68	330	530
T	L0P2	63	70	110	420	402	T	L3P1	49	62	110	180	533
T	L0P3	32	65	80	310	344	T	L3P2	42	52	52	580	536
T	L0P3	55	40	52	350	432	T	L3P2	65	120	213	280	538
T	L0P3	35	60	81	420	501	T	L3P2	68	45	134	280	541
T	L0P3	46	60	163	270	501	T	L3P2	50	40	88	320	544
T	L1P0	35	62	70	250	389	T	L3P3	42	56	73	350	546
T	L1P0	38	51	60	210	292	T	L3P3	55	50	58	330	549
T	L1P0	49	79	99	450	385	T	L3P3	72	72	136	420	552
T	L1P0	46	44	81	240	409	T	L3P3	54	69	124	360	554
T	L1P1	42	76	110	430	549	T	P0-S	49	70	122	370	557
T	L1P1	40	59	95	330	388	T	P0-S	64	74	184	210	560
T	L1P1	38	92	142	480	407	T	P0-S	29	32	52	270	562
T	L1P1	94	51	60	290	413	T	P0-S	39	65	76	410	565
T	L1P2	69	71	160	230	601	T	P1-S	45	50	106	280	568
T	L1P2	89	45	73	410	422	T	P1-S	45	62	148	320	571
T	L1P2	34	51	55	270	420	T	P1-S	47	60	141	460	573
T	L1P2	53	61	188	460	519	T	P1-S	40	50	188	320	576
T	L1P3	70	110	148	560	676	T	P2-S	45	40	202	150	579
T	L1P3	47	60	172	480	500	T	P2-S	44	110	200	270	581
T	L1P3	55	94	233	490	600	T	P2-S	40	82	69	240	584
T	L1P3	52	55	99	410	474	T	P2-S	54	101	125	230	587
T	L2P0	46	42	118	370	428	T	P3-S	36	55	54	270	589
T	L2P0	56	87	165	270	569	T	P3-S	52	120	158	370	592
T	L2P0	47	37	135	350	599	T	P3-S	58	125	78	500	595
T	L2P0	36	60	52	350	364	T	P3-S	40	60	154	330	598
T	L2P1	53	124	188	470	380	T	ALL	35	81	71	330	600
T	L2P1	51	37	136	240	257	T	ALL	29	115	68	300	603
T	L2P1	46	65	100	240	332	T	ALL	36	45	54	280	606
T	L2P1	44	59	108	430	430	T	ALL	32	42	88	290	608

A 1.2 Hairy Canary shoot length across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
HC	L0P0-S	25	54	81	270	611	HC	L2P2	31	70	126	380	330
HC	L0P0-S	27	44	86	290	265	HC	L2P2	31	82	110	230	350
HC	L0P0-S	32	82	118	300	345	HC	L2P2	45	62	90	290	380
HC	L0P0-S	29	55	91	180	220	HC	L2P2	41	86	109	330	410
HC	L0P0	31	65	90	320	350	HC	L2P3	37	73	114	260	355
HC	L0P0	35	76	77	190	320	HC	L2P3	47	79	125	390	470
HC	L0P0	23	46	64	230	362	HC	L2P3	37	87	126	250	270
HC	L0P0	28	53	116	200	335	HC	L2P3	42	72	135	340	360
HC	L0P1	29	54	105	260	215	HC	L3P0	46	53	91	210	245
HC	L0P1	34	63	112	210	335	HC	L3P0	45	84	119	320	365
HC	L0P1	35	74	95	280	315	HC	L3P0	49	80	115	240	360
HC	L0P1	33	89	111	250	335	HC	L3P0	36	96	152	170	410
HC	L0P2	34	92	108	250	230	HC	L3P1	37	78	111	220	315
HC	L0P2	29	104	118	240	360	HC	L3P1	41	79	100	380	425
HC	L0P2	42	86	94	260	340	HC	L3P1	35	82	104	300	365
HC	L0P2	46	84	134	380	270	HC	L3P1	41	105	142	240	340
HC	L0P3	52	84	131	340	355	HC	L3P2	33	61	105	230	430
HC	L0P3	48	74	125	220	460	HC	L3P2	38	92	144	270	350
HC	L0P3	41	63	136	400	390	HC	L3P2	42	75	95	250	330
HC	L0P3	45	135	148	200	380	HC	L3P2	23	70	89	230	360
HC	L1P0	28	60	98	320	265	HC	L3P3	35	82	139	330	395
HC	L1P0	47	102	138	300	315	HC	L3P3	45	89	121	260	330
HC	L1P0	43	68	109	220	410	HC	L3P3	50	72	134	360	460
HC	L1P0	34	65	64	400	290	HC	L3P3	42	80	96	300	425
HC	L1P1	27	83	118	330	500	HC	P0-S	48	65	102	310	345
HC	L1P1	35	59	97	310	410	HC	P0-S	43	82	128	270	475
HC	L1P1	36	91	148	150	450	HC	P0-S	47	82	134	320	420
HC	L1P1	31	70	116	220	400	HC	P0-S	36	76	102	320	390
HC	L1P2	40	78	108	380	430	HC	P1-S	33	100	122	350	345
HC	L1P2	36	77	116	330	350	HC	P1-S	36	101	118	300	410
HC	L1P2	40	98	168	300	410	HC	P1-S	38	96	126	240	430
HC	L1P2	46	65	77	310	385	HC	P1-S	35	69	104	240	355
HC	L1P3	47	74	122	260	375	HC	P2-S	35	76	149	400	305
HC	L1P3	42	88	95	270	340	HC	P2-S	42	71	109	130	470
HC	L1P3	36	82	114	430	365	HC	P2-S	34	84	125	250	450
HC	L1P3	29	90	124	320	405	HC	P2-S	51	87	125	360	405
HC	L2P0	37	76	110	310	405	HC	P3-S	45	91	152	250	350
HC	L2P0	47	100	131	290	430	HC	P3-S	55	94	101	260	430
HC	L2P0	37	73	106	400	455	HC	P3-S	44	74	139	220	460
HC	L2P0	36	104	98	390	475	HC	P3-S	31	91	140	330	365
HC	L2P1	45	72	85	320	430	HC	ALL	41	71	166	300	485
HC	L2P1	35	85	50	320	375	HC	ALL	32	54	159	390	625
HC	L2P1	33	68	89	250	350	HC	ALL	31	44	90	180	440
HC	L2P1	46	70	140	320	435	HC	ALL	32	80	110	190	385

A 1.3 Tagasaste root length across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
T	L0P0-S	28	58	65	120	140	T	L2P2	61	58	139	120	170
T	L0P0-S	44	50	105	130	160	T	L2P2	113	53	72	90	187
T	L0P0-S	44	60	96	190	125	T	L2P2	74	78	40	100	136
T	L0P0-S	54	47	110	190	165	T	L2P2	87	115	75	130	175
T	L0P0	88	51	58	140	142	T	L2P3	44	46	75	120	184
T	L0P0	37	41	95	130	89	T	L2P3	64	66	64	170	125
T	L0P0	43	79	101	120	126	T	L2P3	67	105	118	100	134
T	L0P0	47	51	62	130	115	T	L2P3	51	61	98	110	124
T	L0P1	48	52	76	140	145	T	L3P0	112	96	42	100	169
T	L0P1	59	74	121	120	104	T	L3P0	70	75	71	110	121
T	L0P1	74	60	134	120	135	T	L3P0	58	51	56	100	166
T	L0P1	41	61	85	90	113	T	L3P0	53	88	57	100	180
T	L0P2	70	55	91	150	105	T	L3P1	75	61	54	130	165
T	L0P2	23	82	87	220	121	T	L3P1	54	50	59	100	161
T	L0P2	56	50	51	110	116	T	L3P1	46	72	48	130	161
T	L0P2	25	54	61	110	99	T	L3P1	53	88	61	150	162
T	L0P3	61	50	59	60	141	T	L3P2	50	67	44	110	162
T	L0P3	40	51	50	90	105	T	L3P2	78	86	133	130	163
T	L0P3	42	71	70	110	156	T	L3P2	88	91	82	100	164
T	L0P3	40	40	149	120	90	T	L3P2	59	107	44	110	164
T	L1P0	33	59	78	90	140	T	L3P3	49	68	50	110	165
T	L1P0	38	63	54	140	130	T	L3P3	69	43	31	130	166
T	L1P0	40	61	98	150	148	T	L3P3	82	54	122	110	166
T	L1P0	41	53	51	180	258	T	L3P3	69	111	96	130	167
T	L1P1	49	108	108	100	104	T	P0-S	57	63	68	120	168
T	L1P1	39	68	68	150	142	T	P0-S	69	59	94	90	168
T	L1P1	97	74	92	100	105	T	P0-S	34	67	43	150	169
T	L1P1	51	42	58	120	108	T	P0-S	51	69	101	100	169
T	L1P2	71	82	76	120	134	T	P1-S	48	54	69	90	170
T	L1P2	28	51	90	130	120	T	P1-S	55	55	87	120	171
T	L1P2	70	66	52	140	251	T	P1-S	53	84	98	130	171
T	L1P2	53	64	73	130	126	T	P1-S	44	44	100	120	172
T	L1P3	67	91	114	150	159	T	P2-S	55	59	124	40	173
T	L1P3	84	90	82	160	185	T	P2-S	50	90	116	110	173
T	L1P3	68	87	101	130	154	T	P2-S	60	69	40	50	174
T	L1P3	64	47	66	140	202	T	P2-S	71	78	102	90	175
T	L2P0	53	40	90	130	138	T	P3-S	54	72	39	130	175
T	L2P0	71	77	77	160	80	T	P3-S	62	84	58	120	176
T	L2P0	53	42	128	220	198	T	P3-S	71	93	51	120	176
T	L2P0	59	54	54	130	146	T	P3-S	44	72	97	110	177
T	L2P1	58	116	124	210	189	T	ALL	50	94	58	70	178
T	L2P1	63	42	102	120	91	T	ALL	30	53	68	220	178
T	L2P1	64	75	60	100	176	T	ALL	44	47	51	120	179
T	L2P1	51	98	84	320	92	T	ALL	48	91	52	185	180

A 1.4 Hairy Canary root length across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
HC	L0P0-S	52	100	91	140	180	HC	L2P2	116	96	152	120	220
HC	L0P0-S	92	65	106	240	150	HC	L2P2	83	78	114	100	170
HC	L0P0-S	69	100	140	120	170	HC	L2P2	86	98	152	160	220
HC	L0P0-S	73	97	114	160	200	HC	L2P2	117	88	105	200	160
HC	L0P0	85	60	138	180	340	HC	L2P3	116	87	130	180	340
HC	L0P0	109	70	167	140	180	HC	L2P3	111	80	111	150	240
HC	L0P0	83	84	178	120	230	HC	L2P3	79	63	133	160	195
HC	L0P0	94	67	118	310	150	HC	L2P3	83	70	105	230	310
HC	L0P1	64	121	106	210	215	HC	L3P0	93	71	97	150	195
HC	L0P1	71	60	146	100	255	HC	L3P0	74	74	106	130	185
HC	L0P1	104	61	143	150	155	HC	L3P0	100	50	92	120	160
HC	L0P1	131	63	129	220	220	HC	L3P0	78	96	91	90	290
HC	L0P2	96	98	58	110	210	HC	L3P1	92	65	102	110	1450
HC	L0P2	99	86	101	140	265	HC	L3P1	69	91	192	180	220
HC	L0P2	119	114	162	180	215	HC	L3P1	77	106	109	160	150
HC	L0P2	112	126	111	170	285	HC	L3P1	74	131	105	270	245
HC	L0P3	90	88	118	130	225	HC	L3P2	69	82	152	140	160
HC	L0P3	131	102	126	140	285	HC	L3P2	97	98	117	110	210
HC	L0P3	101	92	131	130	175	HC	L3P2	109	84	120	120	270
HC	L0P3	66	107	106	180	180	HC	L3P2	106	94	114	110	155
HC	L1P0	104	74	136	200	320	HC	L3P3	120	85	78	140	205
HC	L1P0	67	108	117	140	160	HC	L3P3	87	81	134	140	210
HC	L1P0	109	114	98	140	225	HC	L3P3	71	68	116	150	150
HC	L1P0	103	110	162	210	230	HC	L3P3	91	92	91	150	165
HC	L1P1	133	74	178	220	225	HC	P0-S	110	105	84	150	140
HC	L1P1	102	95	120	140	240	HC	P0-S	91	76	109	120	245
HC	L1P1	102	103	146	300	260	HC	P0-S	92	101	109	130	210
HC	L1P1	119	82	123	110	230	HC	P0-S	101	81	131	180	370
HC	L1P2	94	115	95	140	160	HC	P1-S	82	112	166	140	240
HC	L1P2	90	98	171	120	205	HC	P1-S	62	63	140	160	215
HC	L1P2	88	112	121	140	280	HC	P1-S	74	90	130	100	270
HC	L1P2	110	85	148	160	160	HC	P1-S	72	58	151	110	180
HC	L1P3	61	126	144	120	360	HC	P2-S	93	91	89	140	210
HC	L1P3	112	102	94	120	220	HC	P2-S	71	125	146	220	250
HC	L1P3	76	106	117	130	195	HC	P2-S	89	135	105	260	170
HC	L1P3	71	130	127	130	225	HC	P2-S	75	72	136	140	210
HC	L2P0	77	109	104	210	265	HC	P3-S	105	80	156	160	290
HC	L2P0	114	102	96	140	185	HC	P3-S	91	101	134	150	240
HC	L2P0	65	95	141	120	375	HC	P3-S	90	136	102	120	150
HC	L2P0	133	126	82	210	175	HC	P3-S	59	121	165	170	150
HC	L2P1	86	98	126	160	155	HC	ALL	94	109	105	140	200
HC	L2P1	112	119	101	230	205	HC	ALL	71	76	138	170	220
HC	L2P1	78	100	102	200	140	HC	ALL	80	66	121	120	390
HC	L2P1	128	102	145	160	225	HC	ALL	64	70	214	90	260

A 1.5 Tagasaste DM yield across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
T	L0P0-S	0.03	0.09	0.11	0.84	0.76	T	L2P2	0.03	0.10	0.13	1.33	0.88
T	L0P0-S	0.04	0.17	0.22	0.87	1.12	T	L2P2	0.11	0.26	0.37	1.04	1.05
T	L0P0-S	0.04	0.23	0.28	2.39	1.60	T	L2P2	0.07	0.17	0.24	0.89	0.43
T	L0P0-S	0.05	0.07	0.12	0.86	1.55	T	L2P2	0.03	0.28	0.31	1.14	0.92
T	L0P0	0.09	0.19	0.27	0.40	0.61	T	L2P3	0.05	0.15	0.19	0.83	0.94
T	L0P0	0.04	0.08	0.11	0.83	0.85	T	L2P3	0.04	0.16	0.20	1.17	1.92
T	L0P0	0.04	0.18	0.22	1.32	0.84	T	L2P3	0.03	0.10	0.13	1.78	3.35
T	L0P0	0.05	0.08	0.12	0.49	0.98	T	L2P3	0.03	0.08	0.10	0.63	2.00
T	L0P1	0.05	0.17	0.22	0.97	0.59	T	L3P0	0.10	0.08	0.19	1.15	1.52
T	L0P1	0.06	0.24	0.30	0.75	0.96	T	L3P0	0.08	0.10	0.18	0.45	3.19
T	L0P1	0.07	0.12	0.19	0.59	0.99	T	L3P0	0.05	0.15	0.20	0.55	0.79
T	L0P1	0.04	0.08	0.12	0.71	0.49	T	L3P0	0.03	0.09	0.12	0.46	1.86
T	L0P2	0.07	0.20	0.27	2.28	1.19	T	L3P1	0.05	0.07	0.12	0.65	1.58
T	L0P2	0.02	0.30	0.32	2.14	1.02	T	L3P1	0.03	0.12	0.15	0.53	1.97
T	L0P2	0.06	0.09	0.15	0.44	0.85	T	L3P1	0.04	0.16	0.20	0.66	2.72
T	L0P2	0.03	0.16	0.19	0.65	0.81	T	L3P1	0.05	0.15	0.20	0.57	1.06
T	L0P3	0.06	0.18	0.25	0.52	0.85	T	L3P2	0.05	0.10	0.15	1.39	1.45
T	L0P3	0.04	0.09	0.13	0.51	0.99	T	L3P2	0.07	0.29	0.36	0.61	2.40
T	L0P3	0.04	0.19	0.23	1.12	1.99	T	L3P2	0.09	0.08	0.17	0.49	4.19
T	L0P3	0.04	0.08	0.12	0.49	1.98	T	L3P2	0.05	0.12	0.17	0.60	1.41
T	L1P0	0.03	0.11	0.14	0.49	0.94	T	L3P3	0.07	0.06	0.13	0.83	2.98
T	L1P0	0.04	0.13	0.17	0.44	0.74	T	L3P3	0.08	0.07	0.14	0.67	1.01
T	L1P0	0.04	0.23	0.27	0.96	2.18	T	L3P3	0.08	0.19	0.27	1.05	4.18
T	L1P0	0.04	0.10	0.14	0.49	0.96	T	L3P3	0.06	0.18	0.24	0.73	1.66
T	L1P1	0.05	0.18	0.23	1.10	1.46	T	P0-S	0.04	0.18	0.22	0.70	1.91
T	L1P1	0.04	0.22	0.26	0.68	1.10	T	P0-S	0.10	0.15	0.25	0.51	1.55
T	L1P1	0.10	0.22	0.32	0.69	1.35	T	P0-S	0.05	0.06	0.10	0.66	2.52
T	L1P1	0.05	0.14	0.19	0.85	1.11	T	P0-S	0.04	0.10	0.14	0.84	1.66
T	L1P2	0.07	0.18	0.25	0.61	3.16	T	P1-S	0.06	0.07	0.12	0.60	1.38
T	L1P2	0.03	0.06	0.09	1.00	1.08	T	P1-S	0.06	0.20	0.25	1.00	2.06
T	L1P2	0.07	0.10	0.17	0.47	1.60	T	P1-S	0.07	0.17	0.23	1.27	1.66
T	L1P2	0.05	0.18	0.24	0.99	1.51	T	P1-S	0.06	0.10	0.16	0.38	1.77
T	L1P3	0.07	0.29	0.36	2.34	2.98	T	P2-S	0.07	0.06	0.13	0.44	1.85
T	L1P3	0.08	0.19	0.28	0.86	1.62	T	P2-S	0.08	0.13	0.21	0.56	1.49
T	L1P3	0.07	0.23	0.30	1.18	2.30	T	P2-S	0.05	0.15	0.20	0.49	2.39
T	L1P3	0.05	0.09	0.13	0.95	1.79	T	P2-S	0.07	0.21	0.28	0.42	2.83
T	L2P0	0.07	0.09	0.16	0.58	1.82	T	P3-S	0.07	0.11	0.17	0.59	2.19
T	L2P0	0.07	0.21	0.27	1.09	1.99	T	P3-S	0.04	0.39	0.43	0.95	1.21
T	L2P0	0.07	0.10	0.17	1.26	2.80	T	P3-S	0.10	0.16	0.26	1.19	5.80
T	L2P0	0.05	0.16	0.21	0.63	0.88	T	P3-S	0.07	0.14	0.21	0.55	1.72
T	L2P1	0.11	0.18	0.28	1.95	1.05	T	ALL	0.07	0.13	0.20	0.38	1.02
T	L2P1	0.05	0.07	0.12	0.42	0.43	T	ALL	0.03	0.08	0.11	0.60	1.94
T	L2P1	0.05	0.20	0.25	0.47	0.92	T	ALL	0.05	0.06	0.11	0.55	0.68
T	L2P1	0.08	0.24	0.32	1.33	0.94	T	ALL	0.04	0.14	0.18	0.67	1.64

A 1.6 Hairy Canary DM yield across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
HC	L0P0-S	0.02	0.05	0.16	1.09	1.19	HC	L2P2	0.09	0.14	0.22	1.33	3.11
HC	L0P0-S	0.03	0.03	0.19	1.34	1.09	HC	L2P2	0.03	0.09	0.25	0.96	2.25
HC	L0P0-S	0.03	0.08	0.37	0.81	3.14	HC	L2P2	0.03	0.07	0.22	1.33	2.48
HC	L0P0-S	0.02	0.05	0.16	1.32	2.30	HC	L2P2	0.04	0.11	0.19	1.51	2.88
HC	L0P0	0.03	0.07	0.32	0.85	2.03	HC	L2P3	0.06	0.12	0.23	1.34	2.92
HC	L0P0	0.06	0.07	0.19	1.03	2.10	HC	L2P3	0.05	0.08	0.29	1.88	3.35
HC	L0P0	0.04	0.06	0.08	0.97	1.56	HC	L2P3	0.04	0.06	0.29	0.80	1.39
HC	L0P0	0.03	0.05	0.13	1.05	1.23	HC	L2P3	0.03	0.08	0.21	1.15	2.88
HC	L0P1	0.02	0.06	0.19	0.87	2.94	HC	L3P0	0.04	0.06	0.09	0.92	1.14
HC	L0P1	0.02	0.08	0.17	0.96	1.30	HC	L3P0	0.05	0.05	0.19	0.96	2.27
HC	L0P1	0.03	0.13	0.23	0.51	1.29	HC	L3P0	0.03	0.07	0.20	0.65	2.00
HC	L0P1	0.02	0.09	0.26	0.75	1.81	HC	L3P0	0.02	0.17	0.24	0.52	2.45
HC	L0P2	0.04	0.11	0.20	0.52	2.22	HC	L3P1	0.04	0.08	0.37	0.48	1.07
HC	L0P2	0.03	0.14	0.39	0.63	2.20	HC	L3P1	0.03	0.11	0.18	1.90	1.57
HC	L0P2	0.04	0.11	0.29	0.90	2.55	HC	L3P1	0.02	0.09	0.21	0.91	1.56
HC	L0P2	0.03	0.10	0.21	1.13	3.37	HC	L3P1	0.04	0.13	0.29	0.73	1.52
HC	L0P3	0.04	0.09	0.26	0.98	1.37	HC	L3P2	0.02	0.12	0.52	0.49	2.91
HC	L0P3	0.03	0.21	0.41	0.65	2.96	HC	L3P2	0.03	0.10	0.38	0.91	3.55
HC	L0P3	0.07	0.10	0.29	1.21	1.99	HC	L3P2	0.03	0.11	0.19	0.94	1.36
HC	L0P3	0.03	0.17	0.47	1.16	2.06	HC	L3P2	0.03	0.08	0.25	0.67	1.90
HC	L1P0	0.03	0.14	0.24	1.24	2.38	HC	L3P3	0.03	0.17	0.30	1.58	2.00
HC	L1P0	0.06	0.16	0.30	1.05	2.02	HC	L3P3	0.06	0.14	0.45	0.96	1.85
HC	L1P0	0.04	0.11	0.17	0.67	3.06	HC	L3P3	0.04	0.11	0.28	1.86	2.06
HC	L1P0	0.03	0.23	0.24	1.10	2.86	HC	L3P3	0.03	0.10	0.21	1.32	2.39
HC	L1P1	0.06	0.27	0.35	1.44	2.78	HC	P0-S	0.03	0.16	0.17	1.47	1.83
HC	L1P1	0.03	0.09	0.19	1.36	2.19	HC	P0-S	0.05	0.09	0.29	0.78	2.70
HC	L1P1	0.07	0.11	0.24	1.28	2.20	HC	P0-S	0.03	0.15	0.42	0.83	2.08
HC	L1P1	0.04	0.09	0.22	0.92	2.26	HC	P0-S	0.02	0.09	0.34	1.23	2.55
HC	L1P2	0.02	0.16	0.33	0.74	3.20	HC	P1-S	0.02	0.15	0.49	1.46	2.70
HC	L1P2	0.04	0.20	0.41	0.93	1.61	HC	P1-S	0.03	0.11	0.62	1.31	2.61
HC	L1P2	0.05	0.15	0.41	0.80	2.91	HC	P1-S	0.02	0.11	0.56	0.71	3.40
HC	L1P2	0.05	0.08	0.18	1.30	1.53	HC	P1-S	0.03	0.14	0.36	0.74	2.06
HC	L1P3	0.05	0.18	0.35	0.84	4.15	HC	P2-S	0.02	0.07	0.34	1.58	3.22
HC	L1P3	0.06	0.16	0.46	0.79	3.16	HC	P2-S	0.04	0.19	0.32	0.79	3.53
HC	L1P3	0.07	0.23	0.33	0.96	2.28	HC	P2-S	0.02	0.18	0.23	0.88	2.70
HC	L1P3	0.02	0.20	0.20	1.22	1.80	HC	P2-S	0.03	0.15	0.42	0.82	2.22
HC	L2P0	0.04	0.13	0.17	0.69	2.19	HC	P3-S	0.04	0.10	0.43	1.44	2.06
HC	L2P0	0.03	0.17	0.24	1.25	2.89	HC	P3-S	0.04	0.10	0.29	1.10	4.90
HC	L2P0	0.03	0.08	0.38	1.06	2.99	HC	P3-S	0.03	0.11	0.47	1.15	2.66
HC	L2P0	0.04	0.26	0.16	2.19	2.68	HC	P3-S	0.02	0.20	0.38	1.36	3.03
HC	L2P1	0.02	0.10	0.38	1.29	1.86	HC	ALL	0.06	0.18	0.26	1.13	3.22
HC	L2P1	0.03	0.15	0.24	2.05	2.58	HC	ALL	0.03	0.09	0.41	2.05	5.81
HC	L2P1	0.02	0.07	0.20	0.83	2.19	HC	ALL	0.03	0.09	0.24	0.80	3.38
HC	L2P1	0.02	0.14	0.38	0.97	3.35	HC	ALL	0.02	0.08	0.31	0.73	3.33

A 1.7 Tagasaste nodule score across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
T	L0P0-S	1	3	2	2	3	T	L2P2	1	2	1	3	3
T	L0P0-S	1	3	2	2	3	T	L2P2	4	3	1	5	4
T	L0P0-S	1	2	4	3	4	T	L2P2	2	2	1	2	3
T	L0P0-S	1	1	5	2	3	T	L2P2	1	2	2	3	2
T	L0P0	3	2	2	2	3	T	L2P3	1	3	4	2	2
T	L0P0	1	2	2	1	3	T	L2P3	1	3	2	2	1
T	L0P0	1	2	2	2	3	T	L2P3	2	2	3	5	4
T	L0P0	1	2	1	1	3	T	L2P3	1	2	3	2	2
T	L0P1	2	2	2	2	3	T	L3P0	4	3	3	3	2
T	L0P1	1	2	4	1	3	T	L3P0	3	2	3	3	3
T	L0P1	2	1	1	1	3	T	L3P0	1	2	2	2	2
T	L0P1	1	2	3	4	2	T	L3P0	1	2	2	3	3
T	L0P2	1	2	3	4	3	T	L3P1	2	2	3	5	2
T	L0P2	1	2	2	3	3	T	L3P1	1	3	3	3	3
T	L0P2	1	2	1	1	3	T	L3P1	1	2	1	2	2
T	L0P2	1	3	2	2	2	T	L3P1	2	3	2	1	2
T	L0P3	1	1	2	1	4	T	L3P2	1	1	1	2	2
T	L0P3	1	1	2	2	4	T	L3P2	2	4	5	4	4
T	L0P3	1	1	2	1	3	T	L3P2	3	4	2	1	2
T	L0P3	1	1	3	2	2	T	L3P2	2	2	2	2	2
T	L1P0	2	2	2	2	3	T	L3P3	1	1	4	2	2
T	L1P0	1	2	2	3	3	T	L3P3	2	1	1	2	4
T	L1P0	1	2	2	2	5	T	L3P3	4	2	3	2	2
T	L1P0	1	2	2	3	4	T	L3P3	3	2	2	2	4
T	L1P1	1	2	2	4	5	T	P0-S	3	2	3	2	2
T	L1P1	1	2	2	5	3	T	P0-S	3	2	4	2	2
T	L1P1	2	2	2	3	3	T	P0-S	1	1	2	2	2
T	L1P1	1	1	1	2	2	T	P0-S	2	1	2	3	2
T	L1P2	2	2	3	5	5	T	P1-S	1	1	3	5	3
T	L1P2	1	1	1	4	3	T	P1-S	2	2	2	2	2
T	L1P2	1	3	2	3	3	T	P1-S	1	3	2	2	2
T	L1P2	2	3	5	4	2	T	P1-S	2	1	3	5	2
T	L1P3	2	2	2	2	5	T	P2-S	1	1	4	1	2
T	L1P3	4	4	3	3	3	T	P2-S	1	2	3	1	3
T	L1P3	4	2	5	2	3	T	P2-S	1	3	2	3	2
T	L1P3	3	2	3	3	2	T	P2-S	1	5	2	2	2
T	L2P0	2	1	1	3	2	T	P3-S	2	2	1	2	2
T	L2P0	3	3	2	3	3	T	P3-S	2	3	4	1	2
T	L2P0	2	1	3	4	4	T	P3-S	1	4	2	5	3
T	L2P0	1	2	1	2	1	T	P3-S	1	2	4	5	2
T	L2P1	2	3	3	5	3	T	ALL	2	4	2	2	4
T	L2P1	2	2	3	1	2	T	ALL	2	2	2	2	3
T	L2P1	2	2	3	1	1	T	ALL	1	1	2	3	3
T	L2P1	2	2	1	2	2	T	ALL	1	3	3	2	2

A 1.8 Hairy Canary nodule score across five harvests under controlled external and glasshouse conditions in a New Zealand high country soil supplied with increasing lime rates (four levels ranging from 0 – 8 t lime/ha) increasing rates of P (four levels 0 and 500 mg P/kg soil).

Species	Treatment	H1	H2	H3	H4	H5	Species	Treatment	H1	H2	H3	H4	H5
HC	L0P0-S	1	2	1	3	2	HC	L2P2	1	2	1	2	4
HC	L0P0-S	1	1	2	2	1	HC	L2P2	1	1	1	2	2
HC	L0P0-S	1	1	1	3	2	HC	L2P2	1	1	2	1	4
HC	L0P0-S	2	1	1	1	2	HC	L2P2	1	1	2	2	4
HC	L0P0	1	1	1	2	1	HC	L2P3	1	2	2	2	5
HC	L0P0	1	2	2	2	2	HC	L2P3	2	1	1	3	5
HC	L0P0	1	2	2	2	2	HC	L2P3	1	1	3	2	4
HC	L0P0	1	1	1	3	2	HC	L2P3	2	2	2	2	5
HC	L0P1	1	1	1	2	2	HC	L3P0	1	2	1	4	3
HC	L0P1	1	2	2	2	2	HC	L3P0	1	2	1	2	4
HC	L0P1	1	1	2	2	3	HC	L3P0	1	1	1	2	3
HC	L0P1	1	2	1	3	3	HC	L3P0	1	2	1	1	4
HC	L0P2	1	1	1	2	4	HC	L3P1	1	2	1	2	2
HC	L0P2	1	1	1	2	3	HC	L3P1	2	2	1	2	3
HC	L0P2	1	2	1	2	5	HC	L3P1	1	1	1	3	5
HC	L0P2	1	2	1	2	3	HC	L3P1	1	2	2	1	5
HC	L0P3	2	3	2	2	4	HC	L3P2	1	1	3	2	4
HC	L0P3	2	3	3	2	4	HC	L3P2	1	2	2	2	3
HC	L0P3	1	1	3	3	3	HC	L3P2	1	2	2	2	3
HC	L0P3	1	1	2	2	3	HC	L3P2	1	2	2	2	2
HC	L1P0	1	1	1	2	5	HC	L3P3	1	1	1	1	4
HC	L1P0	1	1	1	2	4	HC	L3P3	1	1	2	3	5
HC	L1P0	1	1	1	2	5	HC	L3P3	1	1	1	2	3
HC	L1P0	1	1	1	2	3	HC	L3P3	1	2	1	4	3
HC	L1P1	1	2	2	3	4	HC	P0-S	1	2	1	2	5
HC	L1P1	1	1	2	3	5	HC	P0-S	1	2	1	2	5
HC	L1P1	1	2	1	2	4	HC	P0-S	1	1	2	2	3
HC	L1P1	1	1	1	2	3	HC	P0-S	1	1	1	2	5
HC	L1P2	1	2	1	2	4	HC	P1-S	1	2	3	3	5
HC	L1P2	1	2	1	1	2	HC	P1-S	1	1	4	2	5
HC	L1P2	1	3	2	1	4	HC	P1-S	1	1	2	2	5
HC	L1P2	1	1	2	2	2	HC	P1-S	1	2	1	1	5
HC	L1P3	1	1	2	2	5	HC	P2-S	1	1	1	2	5
HC	L1P3	1	1	2	2	5	HC	P2-S	1	2	3	2	3
HC	L1P3	1	2	2	2	3	HC	P2-S	1	3	2	2	5
HC	L1P3	1	4	1	2	3	HC	P2-S	1	2	3	2	5
HC	L2P0	1	1	1	2	4	HC	P3-S	1	2	3	3	3
HC	L2P0	1	2	1	2	3	HC	P3-S	1	2	3	2	3
HC	L2P0	1	1	1	3	3	HC	P3-S	1	2	2	2	3
HC	L2P0	1	1	1	1	3	HC	P3-S	1	2	2	3	3
HC	L2P1	1	1	2	2	4	HC	ALL	1	2	2	2	5
HC	L2P1	1	2	1	3	5	HC	ALL	1	1	2	2	4
HC	L2P1	1	2	1	3	2	HC	ALL	1	1	2	3	4
HC	L2P1	1	2	1	1	4	HC	ALL	1	2	1	1	5