

**Influence of a legume green manure crop on barley  
straw/stubble decomposition, and soil nitrogen retention  
and availability**

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**A thesis  
submitted in partial fulfilment  
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**D.B. Kapal**

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## **Influence of a legume green manure crop on barley straw/stubble decomposition, and soil nitrogen retention and availability**

By D.B. Kapal

The incorporation of cereal straw/stubble often immobilises nitrogen (N). This can help conserve N in soil in organic forms, thus reducing loss through leaching over dormant winter periods. However, N-depressions that arise during decomposition can reduce crop yield. The inclusion of a legume green manure can supply fixed-N, thus alleviating the low N availability to crops. In this study, the effect of lupin (*Lupinus angustifolius* L.) green manure incorporation on barley (*Hordeum vulgare* L.) straw/stubble decomposition, and N availability was investigated. A field experiment was used to determine the effects of the green manure on decomposition. Decomposition of straw/stubble was monitored using the litterbag technique. Following green manure incorporation, soil cores were incubated in a glasshouse to determine mineral-N availability. Though not significant, the inclusion of lupin green manure seemed to increase the decomposition of straw/stubble during the growth period, then slowing it after its incorporation at 110 d. This was described by a logarithmic pattern of loss of  $-4.97 \text{ g AFDW residue day}^{-1}$ , with 60% remaining after 140 d. Treatments without lupin had a linear decomposition of  $-0.12 \text{ g AFDW residue day}^{-1}$ , with 49% remaining after 140 d. The loss of cellulose confirmed the differences in decomposition with the inclusion of lupin resulting in 2.79% less cellulose remaining in straw/stubble after 140 d compared to its exclusion. Lupin significantly increased pot oat N uptake and DM yield by 55 % and 46 %, respectively, compared to its exclusion. However, this effect was not observed in field sown wheat yields and the soil mineral-N measurements made. This study showed that the potential of lupin to increase straw/stubble decomposition by improving the retention and availability of N, leading to long-term yield benefits, needed further investigation.

**Additional keywords:** Arable cropping, *Avena sativa* L., burning, crop residue, *Hordeum vulgare* L., leaching, *Lupinus angustifolius* L., nitrate, nutrient cycling, organic matter, *Triticum aestivum* L.

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# Chapter 1. Introduction

## 1.1 Background

The pressure to increase crop yield per unit area has intensified as a result of the exponential human population growth, and the steady decrease of land available for crop production due to urban growth and land degradation (Fageria et al. 2006). With the assistance of technological advances, increased global food production on the fixed arable land available has been achieved to address this intensification (Miller 2005; Fageria et al. 2006; Maene, Sukalac et al. 2008). For example, crop production increased by 58 percent between the 1950s and 1990s, while land under cultivation actually declined by six percent (Roberts et al. 2008). In fact by the end of the 1990's, average global cereal production per unit land area under cultivation had increased ten-fold as a result of such yield increases (Maene et al. 2008).

Agricultural advancements that have led to increased productivity include the use of high-yielding crop varieties, chemical fertilisers, farm machinery, and improved crop management practices (Maene et al. 2008). However, the increased production by high-yielding crop varieties, which are more responsive to fertiliser and irrigation (FAO 2003), has often been accompanied by high nutrient inputs (fertilisers) and the removal of half the crop biomass (e.g. grains and straw) (Smil 1999). Such changes have appreciably altered the dynamics of nutrient cycling within the soil-plant system (Byrnes and Bumb 1998; McNeill and Unkovich 2007), with some having adverse impacts upon the environment. In particular, increased fertiliser usage coupled with under-utilisation by crops, has led to the build up of nutrients within the soil profile which then move into ground and surface water causing pollution (Kumar and Goh 2000). Some of these excess nutrients are lost as gases that cause air pollution (Jenkinson 2001). In designing production systems, it is therefore important that management practices are used that can sustain soil productivity, whilst being environmentally friendly or benign.

The sustainability of most crop production systems depends on soil quality, with plant nutrient availability being the most important characteristic (Christensen 2004). When compared to natural ecosystems where nutrients are recycled, most nutrients in cropping systems are removed or lost in harvests, crop residues, erosion, leaching, and gaseous emissions with little returned to the cropping system (Campbell 1998). Hence, cropping systems are more susceptible to nutrient loss than natural ecosystem (Wild 2003) and as such are often supplemented with fertilisers to increase the amount of available nutrients. However, increased applications of inorganic fertiliser along with cultivation can impair the quality of soil, raise the costs of crop production, and have adverse effects on the environment (Fageria and Baligar 2005). To minimise such problems, alternative forms of nutrient input and cropping/cultivation practices are increasingly being utilised. Specifically, soil amendments with manures, crop residue retention and crop rotations are increasingly being practised with the aim of returning nutrients to the soil and increase soil organic matter (SOM) retention (Kumar and Goh 2000). Improving the levels of SOM through the incorporation of crop residues leads to improved soil quality and nutrient cycling while simultaneously providing an alternative means for biomass disposal (Smil 1999).

Soil organic matter is important for conserving and recycling plant nutrients. Vital processes in agroecosystems in particular the conservation and recycling of nitrogen (N) is of paramount importance, since this nutrient is limiting to production in many developed agricultural systems (Christensen 2004). For example, large amounts of N are required to support arable cropping systems, which are ultimately removed in harvests (Fageria and Baligar 2005). Such losses of N, coupled with leaching and atmospheric losses linked with cultivation practices that disturb the soil, are of major concern. Although N leaching is a natural process, increased loads of nitrate in soil-crop system increase the amount lost (Kirchmann et al. 2002). This is particularly important in temperate regions during winter when drainage flux is high and there is limited plant growth to take up the N and protect it from loss (Powlson 1993; Jenkinson 2001). Mitigation techniques used to reduce nitrate concentrations during these periods have been directed at either increased N-use efficiency or improved N conservation (Kirchmann et al. 2002; Sapek 2005). By allowing the conversion of mineral-N to organic N forms in SOM, N can be conserved and protected from loss and thus retained in the soil. In this respect, soil management practices, such as crop residue retention and green manuring, are of particular interest.

## 1.2 Purpose of study

The incorporation of crop residues such as cereal straw which has wide C:N ratios often causes mineral N to be immobilised and bound in the decomposer biomass (Powlson 1993). Such immobilisation of N helps to conserve it in the soil in organic forms for a long period of time, therefore, reducing loss especially loss via leaching (Parkinson 1993). However, the accompanying declines in mineral N availability can affect the yields of subsequent crops and usually have to be mitigated by applying fertiliser-N else organic materials with narrow C:N ratios. Equally, green manuring with legume crops can increase the mineralization of organic N making it available for plant uptake. On the other hand, the flux of available N, if not used quickly by plants, can be lost by gaseous emission or leaching exacerbating the declines in mineral N availability accompanying could assist reduce N-depressions caused by straw decomposition (Christensen 2004).

By providing N which is essential to microbes both through N-fixation and residue incorporation, legume green manures have the potential to substitute for inorganic-N fertilisers that are often used to enhance straw decomposition. It is assumed that the slow decomposition and unavailability of N experienced when residues with wide ranging C:N ratios like cereal straw are incorporated into the soil may be improved by including a legume green manure in the crop rotation. However, little is known about the influence of legume green manures on the decomposition of a cereal crop residue (straw/stubble) and soil-N retention and availability. To study these influences, two straw management practices where residue was either retained or burnt, were compared in the presence and absence of a legume green manure.

## **Chapter 2. Literature Review**

### **2.1 Introduction**

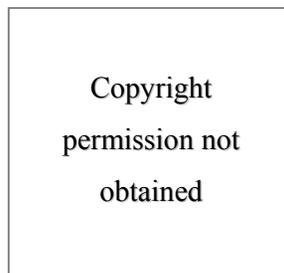
Nutrient cycling in the soil-plant system is paramount for ensuring the health and sustainability of agroecosystems (Marschner and Rengel 2007). As an important attribute of soil quality, nutrient cycling facilitates the availability of nutrients for plant uptake. In this regard, SOM plays a vital role through its influence on nutrient cycling and retention in the soil-plant system (Dick and Gregorich 2004), and it is an intrinsic component of all soil-plant nutrient cycles. With significant amounts of nutrients being removed from arable cropping systems annually in grain crop biomass (Campbell 1998), the retention of crop residues becomes increasingly important as it ensures the recycling of these nutrients, whilst maintaining or improving SOM levels. However, the immobilisation of nitrogen (N) following crop residue incorporation leads to soil mineral N depletions that affect crop production. Such depletions are typically corrected by supplying N fertiliser or organic-N. Alternatively, residues are burned to prevent N immobilisation occurrence.

Nitrogen cycling in agroecosystems is closely related to SOM turnover and cycling (Allison 1973; Christensen 2004). Nitrogen is also the nutrient most limiting to productivity in these systems (Jarvis et al. 1996; Christensen 2004). To sustain crop productivity and maintain soil quality, it is crucial that N-cycling is managed in agroecosystems. Green manures can assist in the recycling of N and other nutrients in cropping systems. The active growth of green manure utilises available N in the soil during fallow periods as well as capturing additional gaseous N through biological N-fixation. Upon incorporation into soil, green manures release N during decomposition that subsequently becomes available for uptake by crops. Green manures, thus help to retain N in the soil, and minimise its susceptibility to loss during winter months in temperate cropping systems.

This review discusses the effects of burning and retention management of crop residues (straw, stubble and green manures) on organic matter and N cycling, and on the bioavailability of other nutrients, focusing on temperate arable cropping systems.

## 2.2 Organic matter cycling in agroecosystems

The transformation of organic matter in soils forms a small but significant part of the overall global carbon (C) cycle. Soil organic matter is the largest C reservoir in agroecosystems as can be seen in Figure 2.1. The major inputs to SOM include plant and animal biomass returns while microbially induced transformation and oxidation through cultivation are responsible for the major SOM losses from agroecosystems. Soil organic matter is a large reservoir of nutrients and its role in nutrient cycling is often linked to soil health and fertility (Jarvis et al. 1996). Mineral nutrients are supplied to plants during SOM turnover, a process important for the improvement and maintenance of soil fertility. Soil microbial population levels and chemical properties of SOM are the main drivers of the decomposition process (Allison 1973). Additional benefits of SOM include its beneficial effect on soil structure and moisture retention/drainage character which condition the soil for nutrient cycling (Stevenson 1994).



**Figure 2.1** Carbon cycling in an agroecosystem (Brady and Weil 2000).

Microbial activity is predominantly responsible for SOM turnover and is generally C-limited in agricultural soils (Murphy et al. 2003). Microbial biomass responsible for these activities make up the active pool of SOM and derive energy from C sourced from recycled plant and animal residues. Microbial populations can increase and diversify as increased quantities of residues of various qualities are added to SOM, speeding up the movement of plant nutrients through the soil-plant systems, which is often a slow natural process (Allison 1973). The slow rates of nutrient movement are also accelerated when land is cultivated, since this serves to expose the SOM to microbial and chemical oxidation.

Movement of crop produce from sites for consumption elsewhere results in limited residue return and therefore reduced microbial C supply (Haynes and Francis 1990; Byrnes and Bumb 1998). By ensuring that SOM levels are optimised, an equilibrium between the rates of nutrient release through microbial activity and removal by crop uptake can be maintained. Therefore, the constant addition of residues is important for SOM improvement, turnover and nutrient release as it supplies C for microbial decomposers and stabilises SOM. The gradual increase of soil organic-C in SOM can also help retain and conserve C, thus reducing contributions to greenhouse gas emissions (Stevenson and Cole 1999; Goh 2004).

In cropping systems, SOM levels can either increase or decrease slowly (Jarvis et al. 1996). However, cultivation increases the rate of decline with some losses being as great as 60 % of the original SOM (Prasad and Power 1997). This results in soil structural problems such as compaction or reduced soil aggregate stability. The latter condition is more common in continued arable cropping systems than in pasture systems or in mixed pasture and cropping systems that utilise grass sods (Allison 1973; Johnston 1991). Continuous annual cultivation in cropping systems leads to the destruction of humic matter with less residues returned to SOM pools (Tan 2003).

The maintenance of SOM at relatively high levels is necessary to optimise plant nutrient supply and soil physical conditions. Soil physical benefits of SOM include increased aggregate stability, improved infiltration and water-holding capacity, and increased drainage and soil aeration (Swift 1991; Nichols and Wright 2004; Havlin et al. 2005). Soil chemical benefits of SOM include pH buffering, increased cation exchange capacity, and

adsorption, desorption, chelation, solubilisation and hydrolysis reactions that enhance nutrient availability (White and Zelany 1986; Chen et al. 1994; Hanes 1997; Weil and Magdoff 2004). Apart from these influences, SOM has indirect benefits such as non-nutrient growth stimulations (Kononova et al. 1966; Chen et al. 1994; Muscolo and Nardi 1997; Nardi et al. 1997), weed and disease suppression (Klöcking et al. 1997; Stone et al. 2004), and the deactivation of organic chemicals and xenobiotics (Schnitzer and Khan 1972; De Simone et al. 1997; Kalbitz et al. 1997). These effects of SOM assist in crop production, while preventing environmental degradation.

Management practices that directly improve and maintain SOM levels in soil include crop rotation, animal manure application, green manuring, and crop residue incorporation. Of these, green manuring and crop residue incorporation are more applicable in continuous arable cropping systems that exclude grass leys (Allison 1973; Goh and Haynes 1986; Kumar and Goh 2000) or animal manures. Plant residues retained in soil can supply nutrients either through immediate mineralisation, or at a slower rate as part of the humification process. Nutrients removed in crop residues can be recycled while green manures add much needed nutrients like N to the active fraction of SOM which aid with decomposition. The fixation of N along with mobilisation of nutrients such as phosphorus (P) by green manure crops (Horst et al. 2001; Fullen and Catt 2004) can also make these nutrients available for subsequent plant uptake.

It is clear that SOM, along with an adequate quantity and balanced availability of macro- and micronutrients required for optimum plant growth, is an important soil quality attribute (Christensen 2004). Furthermore, SOM turnover, although principally a part of the global C cycle, also contains other important nutrient elements that are involved in separate but linked biogeochemical cycles. One such nutrient element is nitrogen. The N cycle is a major cycle, where N availability in the mineral form often controls the rate of decomposition of SOM. Its importance in agroecosystems is discussed next.

## 2.3 Nitrogen cycling in agroecosystems

Nitrogen is an integral element of many essential biological compounds such as amino acids, enzymes, nucleic acids and chlorophyll (Haynes 1986; Brady and Weil 2000). These compounds are building blocks of most living organisms and control numerous biological processes vital for growth and survival. Although abundant in soil, N is often present in forms that are unavailable to plants, especially organic forms (>95 %) which occur in SOM (Allison 1973; Brady and Weil 2000). Less than two percent of the N in SOM is available for plant uptake as mineral-N (Haynes 1986). Only through the process of mineralisation can the organic-N present in SOM be made available to plants (Haynes and Goh 1978; Kumar and Goh 2000; Christensen 2004). Mineralisation and the simultaneous immobilisation of N are important transformation processes in the soil-plant N cycle (Figure 2.2), which is the most important subset of the global N cycle. Biological N-fixation is a transformation process which provides N input to the soil-plant system while other N turnover processes in soil e.g. volatilisation, nitrification and denitrification are pathways for N loss from the soil-plant system.

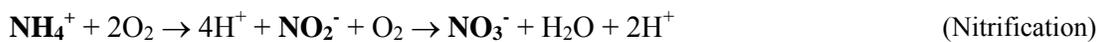
Nitrogen enters the soil-plant system mainly through N<sub>2</sub> fixation, organic matter turnover, plant and animal residue (manure) decomposition, and mineral fertiliser dissolution. Mineral fertiliser application provides the largest N input to agroecosystems (Havlin et al. 2005). However, it is the least sustainable due to the limited long-term benefits on soil physical, chemical and biological properties. Hence, organic N inputs are increasingly perceived as more beneficial. Symbiotic N<sub>2</sub> fixation by the bacteria *Rhizobia* and other microorganisms contribute on average between 112-224 and 30-112 kg ha<sup>-1</sup> yr<sup>-1</sup> of atmospheric N in perennial and short-season annual legumes, respectively (Allison 1973; Brady and Weil 2000; Havlin et al. 2005). Specific examples include a range of 20-173 kg N ha<sup>-1</sup> fixed on average by several annual legumes (Frye et al. 1988), and 70-150 kg N ha<sup>-1</sup> fixed by annual clovers (Sarrantonio and Gallandt 2003).

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**Figure 2.2 Nitrogen flow in the rooting zone of a ‘typical’ arable soil showing major inputs, outputs, and pools of nitrogen (Christensen 2004).**

Large amounts of N are removed from cropping systems through uptake by growing plants, and by leaching and gaseous N losses. Plants use inorganic N from the soil solution namely nitrate ( $\text{NO}_3^-$ ) and ammonium ( $\text{NH}_4^+$ ) ions, and traces of nitrite which are made available through mineralisation (Vinten and Smith 1993; Kumar and Goh 2000). Nitrate is usually the dominant form of plant available N in agricultural (oxidised) soils due to the rapid oxidation of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  (Fageria and Baligar 2005; McNeill and Unkovich 2007), and particularly in arable soils where  $\text{NO}_3^-$ -N is most preferred (Haynes and Goh 1978; Haynes 1986; Vinten and Smith 1993).

Mineralisation involves the liberation of ammonium ( $\text{NH}_4^+$ ) from organic-N compounds, often termed ammonification (McLaren and Cameron 1996). This process is often followed closely by oxidation of  $\text{NH}_4^+$  into nitrate ( $\text{NO}_3^-$ ) (nitrification) (Smith et al. 1993; Vinten and Smith 1993). The opposite is true during immobilisation where the conversion of mineral N back into organic N by microorganisms occurs, often simultaneously with mineralisation. The net balance between both opposing processes determines the rate of mineral N (and other nutrient) release (Kumar and Goh 2000; Pierzynski et al. 2005). The two-part conversions in the mineralisation process are:



Most N turnover processes such as mineralisation are dependent on microbially mediated transformations, often in association with SOM turnover (Jenkinson 2001; Christensen 2004). N-turnover in the decomposer biomass and labile organic matter is considerably faster than that in stable organic matter. Microbes respond readily to plant residue and animal manure application and soil disturbance such as tillage. The residues and manures added often have narrow ranging C:N ratios (25:1 or less) (Rahn et al. 2003; Wolf and Snyder 2003) that provide microbes with energy, while tillage exposes SOM to microbial access and oxidation.

Given the importance of soil microbes in N transformation and turnover, organic sources of N need to be properly managed to provide an environment conducive for microbes (Pierzynski et al. 2005). This can be addressed through SOM improvement, which tends to induce optimum microbial activity through its effects on soil physical, chemical, and biological properties (Kumar and Goh 2000). Although the mineralisation of N from SOM provides a significant portion of the N required by plants, it is inadequate to achieve economically optimum yields for important agricultural crops (Gasser 1982). However, the long-term use of manures or leguminous rotational crops can greatly increase the amount of potentially mineralisable organic-N in soils, leading to markedly reduced fertiliser N requirements (Kumar and Goh 2000; Pierzynski et al. 2005). Though the reduction of the latter is considered important from economic and environmental perspectives, the overall increase in N inputs to the N cycle is still a liability (O'Hara 1998). In this respect, the doubled global N fixation rate caused by anthropogenic management or interference in the

N cycle has intensified nitrous oxide ( $N_2O$ ) production during microbial nitrification and denitrification (Jenkinson 2001; Bergström et al. 2005), and increased nitrate-N leaching from agroecosystems. The existence of nitrate-N in the soil is often short-lived due to its susceptibility to denitrification and loss through leaching (Haynes 1986). Considering the dominance of nitrate-N in cropping systems, any practice that either improves the efficiency of nitrate-N use, or allows it to be converted into organic forms thereby reducing losses from the system, is worthy of investigation.

## 2.4 Nitrogen dynamics in temperate arable cropping systems

In temperate cropping systems, reduced cropping intensity during winter, coupled with increased moisture and net water percolation down the soil profile creates a high potential for N loss (Bergström and Kirchmann 2004). Leaching occurs naturally, however, the increased loads of nitrate-N released from agroecosystems owing to the accelerated N cycling in managed agroecosystems augment the quantities leached (McNeill and Unkovich 2007). Nitrate-N that is not leached remains in soil but can be further lost through denitrification, owing to the anaerobic conditions created by high soil moisture conditions, therefore, increasing gaseous losses. Such losses of N can be mitigated by reducing nitrate concentrations in soil during winter through increased crop N recovery and transformation into organic-N (Sapek 2005).

The cropping system dominant in the Canterbury Plains of New Zealand is one in which 2 to 4-years of fertility-depletive cereals and other cash crops are rotated with 2-4 years of grazed pastures (Haynes and Francis 1990; Roberts et al. 2008). Continuous cropping on the same site during the arable phase of such a system often depletes readily mineralisable-N and hence additional inputs of N are required (Gasser 1982; Kumar and Goh 2000). For example, up to 190 kg N ha<sup>-1</sup> can be removed in wheat grains and straw in a 10 t ha<sup>-1</sup> grain yield crop (Haynes and Francis 1990), and this needs to be replaced.

Crop rotations with nutrient returning crops such as legumes are common. However, where their use is limited, inorganic fertilisers are used to replace the N lost from arable cropping systems. The inclusion of legume crops, whether in rotations or in grass-legume leys, ensures a more sustainable system with the capacity to fix atmospheric N while improving SOM and ultimately the soil. N-fixation contributes to agricultural production through the use of legumes as green manures, legumes as cash crops, and legumes as forage crops (Goh and Haynes 1986; Kumar and Goh 2000). Symbiotically fixed N can thus be transferred to other crops, with the use of legume as a green manure maximising this transfer.

Cultivation during the arable phase is necessary for land clearance and seedbed preparation. The ploughing under of pastures, catch (or cover) crops, crop residues, and green manures not only introduces new SOM to the soil-crop system, but also exposes old SOM for oxidation and microbial attack. Cultivation therefore greatly increases the rate and amount of N made available through mineralisation. At the same time, microbial immobilisation of N released during decomposition can significantly depress mineral N availability and reduce crop yield. The decomposer microbes that breakdown residues, especially those high in lignin, immobilise N, therefore, reducing the amount of mineral N available to plants.

Residues with high N and low lignin and polyphenol concentrations can be decomposed rapidly, with large amounts of N released; while those low in N, but with large lignin and active polyphenol concentrations decompose and release N slowly (Handayanto et al. 1997; Kumar and Goh 2000). The former meet the immediate N demands of crops but contribute little to SOM maintenance, while the latter lock up most of the N in soil, releasing it slowly over time. An option to balance these effects is to co-incorporate materials of wide ranging C/N ratios with those with narrow ranging C/N ratios as this has shown to reduce N leaching (Rahn et al. 2003). However, the retention of plant material in soil has both advantages and disadvantages, and specific management options would be needed to satisfy the N requirement of different cropping systems. The next sections discuss management options for cereal residues (straw/stubble), and green manure, and their effects in arable cropping systems.

### **2.4.1 Residue (straw/stubble) management**

Straw is a tough fibrous material that is resilient to decomposition (Staniforth 1982). Its fibres are made up of cellulose strands bound in a matrix of hemicellulose and lignin, making them partially protected from decay (Summers et al. 2003). Together cellulose, hemicellulose and lignin make up 80 % of the chemical constituents of straw (Table 2.1). With such properties, the incorporation of a heavy crop of straw into soil will make it dry and less compact, impeding the movement of moisture (water repellent) (de Jonge et al. 2007) and nutrients (Staniforth 1982). However, this problem can be solved by thoroughly breaking up and mixing straw with moist and well aerated soil at a sufficiently high temperature so as to encourage breakdown.

**Table 2.1 Chemical constituents of straw (Butterworth 1985).**

	Approximate %	Breakdown rate
Water soluble materials (e.g. sugars)	8 – 12 (6*)	Days
Cellulose ( a polymer of glucose)	38 – 44 (40*)	Months
Hemicellulose (a polymer of glucose & other sugars)	32 – 36 (39*)	Months
Lignin (a polymer of phenols)	10 – 15 (13*)	Years

\*Proximate chemical composition of barley residues (Lynch 1979). Values as % of dry weight.

Straw disposal has become a problem due to changes in farming methods, particularly where mixed animal and crop farming has been replaced by agriculture specialising in either crops or animals (Ellis 1979). Historical usages of straw for livestock feed and bedding has declined thus increasing the amount that needs disposal. In New Zealand, baling and burning have been the traditional disposal methods (Beare et al. 2002). Given an average of 6 t ha<sup>-1</sup> of cereal grains were harvested from a 12 t ha<sup>-1</sup> crop (mean harvest index (HI) of 0.5), a quantity of 6 t ha<sup>-1</sup> of cereal residues produced would either be burnt or baled (MAF 2004). However, the removal of cereal residues is fast changing as farmers become more aware of the problems of soil organic matter and nutrient loss (Kumar and Goh 2002), and air pollution (Smil 1999). Soil incorporation of straw/stubble is an option that is being accepted by many farmers as a means of addressing the disposal problem.

### 2.4.1.1 Burning

Burning of straw/stubble is widely practised around the world and for various reasons, with reduction of crop residue biomass, and control of weeds, pests and diseases being the main ones (Campbell 1998; Smil 1999; Kumar and Goh 2000). In New Zealand, where cereal production is high (Roberts et al. 2008), burning is often practised to clear land, reduce grass weeds like brome (*Bromus sterilis/Bromus commutatus*), eliminate slugs, and reduce diseases such as ‘take-all’ in wheat-wheat rotations (FAR 2006). Burning is the quickest and easiest method of land clearance. The reduced cost of land preparation and drilling make burning more appealing and practical. Furthermore, burning helps to reduce weed pressure, and eliminate pests and diseases through sterilisation (Staniforth 1982; Butterworth 1985), thereby reducing the input of herbicides and pesticides. The ash obtained from straw burning contains nutrients such as potassium (K) and phosphorus (P). In addition, N from soil microbes killed during the burn is returned to the soil, often resulting in vigorous growth of subsequently planted crops.

Crop yield improvements associated with burning have been attributed to nutrient release and reduced weed, pest and disease occurrence. For example, long-term trials in Letcombe showed high yields of winter wheat where straw residues had been burnt, compared to plots where residues had been retained (Butterworth 1985). More recently, Chan & Heenan (2005) reported improved wheat yields following stubble burning in a 19-year trial in South Australia.

However, the benefits of burning have gradually been overshadowed by the increasing concerns over air pollution and soil degradation as SOM and nutrients are lost in the process via erosion and volatilisation. In Canada, Biederbeck *et al.* (1980) found that a normal burn resulted in 32 % and 27 % loss of straw dry matter and N content, respectively. Although results from some long-term trials showed no changes in SOM content when burning was compared with other methods of disposal (e.g. (Staniforth 1982)), return of any crop residue is beneficial for SOM maintenance and nutrient cycling. Apart from C, N and sulphur (S) are almost entirely lost from the soil-crop system during combustion of straw/stubble (Smil 1999). Other nutrients such as P are either retained on the ground (Biederbeck et al. 1980), or in airborne particles that drift no more than 10 to 100 m (Campbell 1998). The nutrients that remain on the soil surface are prone to erosion

before plant recolonisation takes place. The oxides of some nutrients such as K and calcium (Ca) can increase soil pH when hydrolysed (Campbell 1998).

Apart from its effects on SOM and nutrients, fires pose a threat to flora and fauna, infrastructure and even lives when not controlled. A more subtle problem that results from long-term burning is the reduced number and activity of deep-burrowing earthworm, along with other surface- and soil-inhabiting invertebrates and this can lead to soil structural problems (Edwards and Lofty 1979). Reduced microbial activity after a fire and SOM destruction add to the problems associated with soil fertility loss. In arable cropping systems, where the loss of organic matter is rapid due to continuous cultivation, burning can amplify this loss. For this reason, and also because of atmospheric pollution issues, stubble burning is being phased out in numerous parts of the world.

#### **2.4.1.2 Retention and incorporation into arable cropping systems**

Straw contains a fair amount of nutrients as shown in Table 2.2, and its retention in arable cropping system has been an option that has been explored with various outcomes. The benefit it bestows in terms of improved long-term productivity is mainly due to the addition of organic matter, which is particularly important in lighter textured soils (Butterworth 1985). Since organic matter decomposition in soil is a microbial process, increased microbial activity results as energy sources in the form of residues are added to soil. Microbe activity is affected by factors such as moisture, temperature, aeration, straw length, and nutrient availability, N in particular is required for decomposition. Under optimum conditions, nutrients in crop residues are recycled and gradually become available for crop uptake as the residues are decomposed.

**Table 2.2 Nutrients contained in stubble from a 2 t/ha crop of wheat (Hermann 1992).**

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The gradual release of nutrients from cereal straw does not often produce yield increases by subsequent cereal crops. However, the conditioning effect that new organic matter has on the soil appears to improve nutrient uptake. Cereal straw incorporation has been found to increase the uptake of N, P and K by succeeding wheat crops even though yields were not increased (Fullen and Catt 2004).

Populations of other organisms that aid decomposition such as fungi, earthworms, and other invertebrates will also flourish as a result of straw incorporation (Lynch 1979); (Curry and Byrne 1997). Soil physical properties such as aggregation and moisture retention can be improved through this practice. Improved soil fertility should ultimately lead to reduced fertiliser requirements, reducing the costs of inputs. Other benefits such as reduction in wind and water erosion result either directly from straw/stubble mulch or because of the SOM increases straw incorporation produces (Douglas and Rickman 1992).

Although the long-term incorporation of straw/stubble is beneficial, numerous immediate problems are associated with this practice. The most obvious problem is the physical impediment straw, stubble or chaff residues present to mechanical cultivation equipment that can lead to high costs of cultivation when compared to burning. Another problem is that straw residues can inactivate herbicides, making weed eradication more difficult and costly (Schnitzer and Khan 1972; Kumar and Goh 2000). The presence of pests and diseases in crop residues can also be a problem for new crops, while the release of toxins from the decomposition of straw/stubble can interfere with germination and plant growth. Not only will the toxins retard growth, but N immobilised by microbial biomass when cereal residues with wide ranging C:N ratios (>80:1) are incorporated in soil can lead to yield depressions in subsequent crops (Allison 1973; Kumar and Goh 2000). Refusal by farmers to incorporate straw/stubble is often due to fears of such yield losses occurring (Beare et al. 2002). However, if straw/stubble is used in combination with other organic soil amendments such as slurry, green manure and catch crop or application of N fertiliser, the risk of yield depression is significantly reduced. Thomsen and Sorensen (2006) associated this yield depression reduction with the long-term contribution of stubble residues to SOM whose decomposition was aided by the high N residues that were co-incorporated. Fullen and Catt (2004) found that the application of 2-6 kg of N per tonne of straw was enough to off-set immobilisation during the decomposition process. As an added benefit, the incorporation of material with wide ranging C/N ratios along with high lignin

and polyphenol like cereal straw/stubble, have been shown to effectively lower N available for nitrification and denitrification, thus reducing loss from soil-crop systems (Kumar and Goh 2003; Sarkodie-Addo et al. 2003).

Regardless of problems with the practice, more farmers are considering straw incorporation as a way of managing SOM better and allaying public concerns over the impacts of straw burning on air pollution (Beare et al. 2002).

## **2.4.2 Green manure and its role in N dynamics**

The re-emergence of the age-old practice of green manuring is mainly due to the increased knowledge of the ecological principles involved. This, along with increasing costs of agricultural inputs, particularly following the energy crisis and rising fertiliser costs in the 1970's (Frye et al. 1988) and the need to address the global problem of soil degradation (Sarrantonio and Gallandt 2003), has propelled the re-emergence of this practice. Green manure, according to Allison (1973), includes any plant material turned into the soil while still green (before physiological maturity) for the primary purpose of improving soil fertility. In particular, it refers to legumes grown to enhance the short-term N fertility of the soil (Sarrantonio and Gallandt 2003). However, green manure also includes other non-legume crops that are turned under before or near maturity while still green, but which were sown originally for cover, break or catch crops (Magdoff 1992; Kumar and Goh 2000).

In temperate arable cropping systems, legume green manure crops play an important role in the N dynamics of the soil-crop system, mainly through their ability to biologically fix  $N_2$  and utilise residual N. Grown typically through the autumn – winter period when the potential for leaching is high, green manures reduce loss from soil by acquiring additional plant available N. This is largely due to the good root systems developed by such crops that enable the crops to capture nitrate-N at both shallow and deeper depths which would otherwise be lost by leaching or denitrification (Stevenson and Cole 1999). Crops such as lupin (*Lupinus* spp. L.) have been shown to be as effective as cereals in taking up N, as well as fixing atmospheric N (Fowler et al. 2004). After the green manures are ploughed into the soil in late winter – early spring, N either fixed or taken up by the green manure crop is released through decomposition and becomes available to subsequent crops. The increased supply of readily degradable organic matter in the green manure supports large microbial populations, which in turn increase the rate of oxidation of soil organic matter facilitating the release of N and other nutrients for crop uptake (Stevenson and Cole 1999).

Apart from supplying nutrients, the addition of green manure to SOM results in improved soil physical properties such as better aggregation, water infiltration, aeration, and moisture retention. Furthermore, chemical properties like cation/anion exchange, pH buffering, and

chelation, adsorption and complexing reactions are also improved (Thorup-Kristensen et al. 2003; Wolf and Snyder 2003). The incorporation of green manure does not always improve yields immediately, but over time they do often increase significantly due to the gradual improvement in SOM quantity and quality (Stevenson and Cole 1999; Stark et al. 2006). The added benefit of green manure in terms of weed suppression and pest and disease control further assist with yield improvements and more over reduce costs of chemical (pesticide and herbicide) inputs (Allison 1973; O'Hara 1998).

The bioavailability of N following green manuring is largely microbially mediated, and is consequently dependent on factors that affect microbial (particularly bacterial) activity (Sarrantonio and Gallandt 2003). These include soil moisture, temperature, microbial access to substrate, and pH, which in turn are influenced by weather, soil type, tillage, and residue size and composition (Thorup-Kristensen et al. 2003). Most of these factors can be manipulated through manipulating the SOM content of soil.

The timing of application and the quality of green manures are more important than the quantity, as the former factors influence mineralisation and the ability of crops to utilise the N and nutrients released. In cropping systems, the timely use of high N containing green manure in combination with low N materials will allow for the manipulation of net mineralisation to ensure a steady cycling of N within the system (Kirchmann et al. 2002). Wagger (1989) found that when ploughed into the soil before maturity, legumes had lower dry matter but higher N concentration and low C/N, and that decomposition was faster. On the other hand, the high cellulose, hemicellulose and lignin contents of legumes ploughed in at a matured age reduced the speed of decomposition. Immature green manure crops have high levels of sugars, starch, amino acids and proteins present and narrow ranging C:N ratios that are close to those of microorganisms (10:1) than those of mature materials (>25:1) (Wolf and Snyder 2003).

Legumes have been shown to provide nutrients other than N, including P from sources not accessible to many non-leguminous plants (Fullen and Catt 2004; Wasaki et al. 2008). Ohno and Gannel (1996) found that increased dissolved organic C in green manure increased the bioavailability of P by releasing aluminium (Al) adsorbed onto surfaces of complexes, which in turn reduced the potential for P complexation by Al. Randhawa *et al.* (2005) reported a daily gross organic P mineralisation of 0.27 mg P kg<sup>-1</sup> from lupin green

manure amended soils. This efficiency was a result of the ability of lupins to produce exudates that mobilise P from available, acid and also stable residual soil P fractions (Kamh et al. 1999).

Legumes are known to contain significant amounts of P, K, Ca, Mg, Boron (B) and Molybdenum (Mo) (Seiter and Horwath 2004; Wolf and Snyder 2003), which are all released upon legume residue and microbial biomass decomposition. Nutrient recovery from green manures varies with different environmental factors (e.g. climate, soil conditions), type of management (e.g. shredding, mixing, soil incorporation) and tissue quality characteristics (e.g. C, N, cellulose, lignin, polyphenol contents). When managed well, green manures can assist in maintaining soil fertility by improving SOM content and nutrient release, ultimately leading to improved production in arable cropping systems.

## **2.5 Hypotheses and Objectives**

Studies on the use of green manures to alleviate N depressions reviewed so far have not looked at incorporating a green manure crop during straw/stubble decomposition at the same site immediately after the cereal crop harvest. Straw management practices and the use of green manures have either been studied individually or together but with the treatments such as green manure and straw being grown separately elsewhere and brought together at the site of study. The effects of a growing green manure and its subsequent incorporation into the soil on straw/stubble decomposition at the same site need to be investigated. Particularly, the influences these practices have on N and its availability to plants. Hence, the following hypotheses and objectives were arrived at.

### **2.5.1 Hypotheses**

- i. The retention of cereal straw/stubble compared to the practice of burning will improve N retention in the soil, thereby preventing loss.
- ii. The inclusion of a legume green manure in the crop rotation will significantly increase the decomposition of straw/stubble by increasing N availability through N-fixation and mineralisation.
- iii. The inclusion of a legume green manure will significantly increase overall N-mineralisation and plant availability.

### **2.4.3 Objectives**

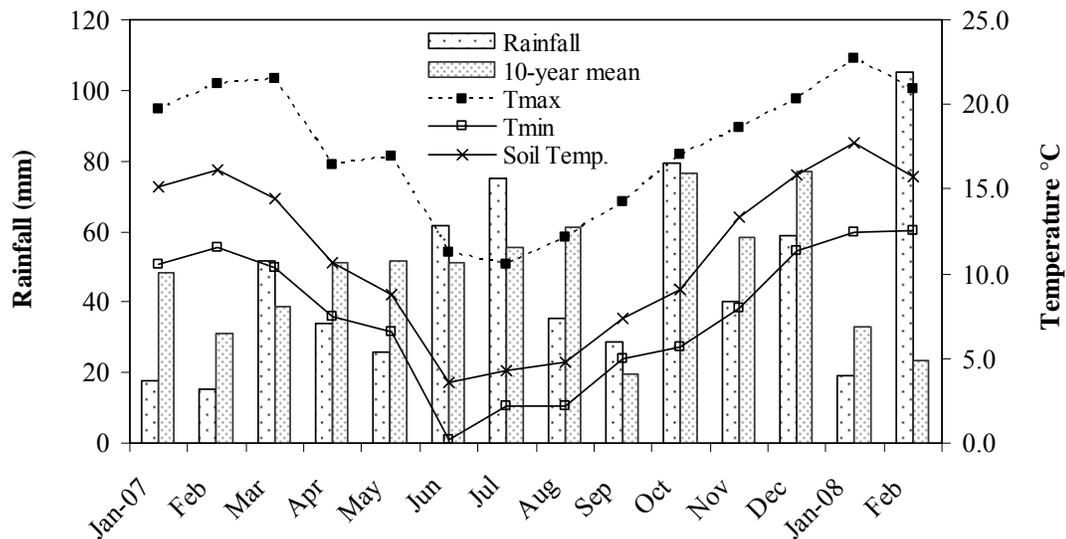
- i. To measure the effects of cereal straw/stubble inclusion and burning on N retention and availability in the soil;
- ii. To measure the effects of a legume green manure incorporation on straw/stubble decomposition;
- iii. To measure the effects of a legume green manure incorporation on overall N-mineralisation and plant availability.

## Chapter 3. Materials and methods

### 3.1 Trial site

A 1.08 ha area in the Horticultural Research Area (HRA) at Lincoln University was used for the field experiments. The Templeton sandy loam soil (immature pallic soil) (NZ Soil Bureau 1968) had previously been cropped with nutrient depletive crops, with ryegrass (*Lolium multiflorum* L.) the last grown, and had a pH of 5.80, 1.91 % C and 0.164% N at the beginning of this study. Spring barley (*Hordeum vulgare* L.) was sown on the trial area in September 2006, and grown to maturity with 50 kg N ha<sup>-1</sup> applied after sowing. At harvest in February 2007, the crop produced a yield of 7.38 t ha<sup>-1</sup> of grain and 5.99 t ha<sup>-1</sup> of straw.

Monthly rainfall, minimum and maximum air temperatures, and soil temperature at 10 cm depth, which were recorded during the study period, are shown in Figure 3.1.



**Figure 3.1** Total rainfall, minimum, maximum air temperatures, and soil temperature at 10 cm depth recorded between January 2007 and February 2008. Source: Broadfield, Crop and Food, Lincoln, NZ from Cliflo database.

## 3.2 Field experiment

The first objective of the decomposition experiment was to determine the effects of decomposing straw/stubble on nitrogen retention and availability in the soil. This was achieved by measuring the decomposition of straw/stubble in litterbags over 5 months (autumn-winter), along with total N and mineral N in the surrounding soil. The second objective was to determine the effects of incorporating a legume green manure on straw/stubble decomposition. The legume used in this study was *Lupinus angustifolius* L. var. Blue Lupin that was tolerant to low temperatures and would be ready for ploughing in after 4 months. The agronomic yield and nutrient contents of the green manure were measured before it was ploughed in.

A randomised complete block design was used to test four treatment combinations, each of which was replicated four times giving a total of 16 plots. Net plot areas were 135 m<sup>2</sup> (9 m x 15 m) each, giving a total trial area of 2160 m<sup>2</sup>. The plots had 5 m spacing between them to allow access by machinery. The four treatment combinations were:

- (i) Straw/stubble burned with legume green manure (B+L);
- (ii) Straw/stubble burned without legume green manure (B-L);
- (iii) Straw/stubble retained with legume green manure (S+L);
- (iv) Straw/stubble retained without legume green manure (S-L).

The treatment combinations were applied as follows. At the barley harvest in February 2007, the straw was threshed and spread as evenly as possible over all plots. The average rate of straw/stubble application was 5.99 t ha<sup>-1</sup>, however, some spots had coverage rates measuring up to 7 t ha<sup>-1</sup> as can be seen in the foreground of Figure 3.2. Barley straw/stubble on plots with treatment combinations (i) B+L and (ii) B-L were burned using a tractor-mounted gas flame weeder for a more controlled and consistent burn (Kumar and Goh 2002). All straw/stubble was retained in plots with treatment combinations (iii) S+L and (iv) S-L.

Light discing was done on all plots after straw/stubble treatment application, following which the legume green manure crop were sown into plots with treatment combinations B+L and S+L. Straw/stubble burning and legume sowing were all completed between the 5<sup>th</sup> and 8<sup>th</sup> of March 2007 (autumn). All weeds in plots without lupin (B–L and S–L) were controlled with glyphosate herbicide (Roundup®). At the end of July 2007 (winter), the legume green manure was rotary hoed in the B+L and S+L treatment plots. All 16 plots were then ploughed to a depth of 20 cm.



**Figure 3.2** Plots with straw retained (foreground) and those being burned (background) during treatment application on March 5 2007.

### **3.2.1 Straw/stubble decomposition**

Straw/stubble decomposition in 8 of the 16 plots with straw/stubble retained treatments S+L and S-L were monitored using litterbags by the method described by Beare *et al.* (2002). Fibreglass-nylon litterbags (20 x 20 cm, 4-mm mesh) were filled with 30 g of oven-dried (65°C) postharvest barley stems and leaves cut to 5-cm lengths, giving a straw/stubble application rate of 7.5 t/ha. These were then buried horizontally at 10 cm depth directly following lupin sowing on March 9, 2007. Lupin seeds were removed, litterbags buried after which the seeds re-sown. The chemical composition of the straw/stubble used in the litterbags is presented in Table 3.1.

Two litterbags were sampled from each plot at 10, 50, 80, 110, 120, 130 and 140 days after burial between March and August 2007 (autumn-winter). Sampling at 110 days corresponded with the time of green manure incorporation. All remaining litterbags were removed and stored at 4°C, then reburied immediately after lupin incorporation. This was to be completed simultaneously between June 27 and 29 2007, however due to very wet field conditions, lupin was not turned under until 4 weeks (20 days) later in July 25 2007. The 4-week 'out of the ground' period was not counted as there would be no decomposition.

Residues from the litterbags were sieved (1 mm), weighed and oven-dried at 70°C for 48 hours before being ground using a Cyclotec 1093 sample mill. Two sets of subsamples (0.5 g) of the ground residues were ashed in a muffle furnace at 550°C for 5 hours to determine the ash content (Beare *et al.* 2002). The averaged ash contents were then used to adjust weights as ash-free dry weights (AFDW) and N content to account for contamination. These was done by determining the percentage ash content of samples, then subtracting the weight or percentage N content to get final ash-free weights and N contents. The AFDW values obtained were then used to determine the amount of litter decomposed by weight loss. Total C and N of the ground residues were determined using a LECO C/N/S analyser, while lignin and cellulose contents were determined using the acid-detergent fibre (ADF) proximate analysis described by van Soest (1994).

**Table 3.1** Chemical composition of initial barley straw/stubble placed in litterbags.

Total C	Total N	C/N	Ash	Organic matter	Lignin*	Cellulose*
46.06 %	0.58 %	80	5.7 %	94.3 %	6 %	44.1 %

\*Proximate analysis reported on the basis of organic matter content of straw/stubble.

### **3.2.2 Green manure production**

Blue lupin was sown in early autumn (March 8, 2007) at 160 kg/ha into plots with treatment combinations B+L and S+L. Lupin was sampled at the end of June 2007 just before flowering at 16 weeks old. Two sets of above ground biomass samples (inclusive of weeds) were taken from each of the 8 treatment plots, using 0.204 m<sup>2</sup> quadrants. No sample was collected from plots with B-L and S-L treatments, as they had had herbicide applied. The above ground biomass samples collected were grouped as lupin, carryover barley and other weeds. These were weighed separately before being dried at 65°C for 48 hours. The dry weights of the 3 groups were recorded separately for dry matter and yield determination. All samples were then ground using the Cyclotec 1093 sample mill. Total C and N in lupin and barley were measured using a LECO C/N/S analyzer.

### **3.2.3 Nitrogen availability**

The availability of N in soil was determined by measuring total C and N, and mineral-N. Soil was sampled the same day litterbags were retrieved. Soil sampling that coincided with litterbag retrieval at 140 d was in fact taken 160 d after straw/stubble incorporation, henceforth referred to as sampling at 160 d. The discrepancy in days was due to the 20-days (4 weeks) ‘out of the ground’ period for the litterbags. Six cores (3.0 cm inner diameter) were taken at two soil depths (0–7.5, 7.5–15 cm) per plot with samples from each depth bulked separately, giving a total of 32 samples (8 per treatment combination). After moisture determination, all samples were sieved (2 mm) and split into two and half dried while the other half was stored at 4 °C for subsequent chemical extraction.

Ammonium-N and nitrate-N were extracted from the field moist samples with 2M KCl, using 5 g of field moist soil and with 40 ml of KCl, according to the method described by Blakemore *et al.* (1987) and Beare *et al.* (2002). All extracts were stored in a deep freezer (<-20 °C) to prevent microbial degradation (Clough *et al.* 2001) until analysis when they

were thawed. Analysis was done using the Alpkem FS3000 twin channel flow injection analyser (FIA). Total C and N of air-dried soil samples were analysed using a LECO C/N/S analyser.

### **3.2.4 Soil pH**

The pH of soil samples were analysed by mixing 10 grams of air-dried soil with 15 ml deionised water and allowed to stand overnight before pH determination (Blakemore et al. 1987).

### **3.3 Glasshouse experiments**

The overall effects of the treatment combinations on N mineralisation and crop availability were determined in a glasshouse using soil cores taken from the field after green manure incorporation. Two methods of determination were employed: (1) a leaching experiment to determine the rate and amount of N released, and (2) a pot trial to determine N uptake by a crop.

#### **3.3.1 Soil cores**

Two sets of re-constituted soil cores (16 cm diameter x 16 cm depth) were taken from each plot (total 32 cores) on July 25, 2007, 3 days after the incorporation of green manure. Due to the rotary hoeing of all plots during lupin incorporation, intact soil cores could not be collected. Instead, soil was packed into lysimeter casings using a spade, a modified version of the method described by McLenaghan *et al.*(1996). Two spadefuls of soil, and plant residues, were collected in a bucket. From this bucket, a marked container was used to fill the lysimeters, pre-packed with sand to 5 mm from the base to assist filtration and prevent clogging. The volume of all cores collected was kept constant at approximately 2.5 litres of soil per core. The cores were transferred to a glasshouse and set up for N mineralisation and N availability measurements between August and October 2007 (winter-mid spring) (Figure 3.3). The minimum and maximum glasshouse temperatures during this period were 14°C and 20°C, respectively, and the mean temperature was 18.8°C.

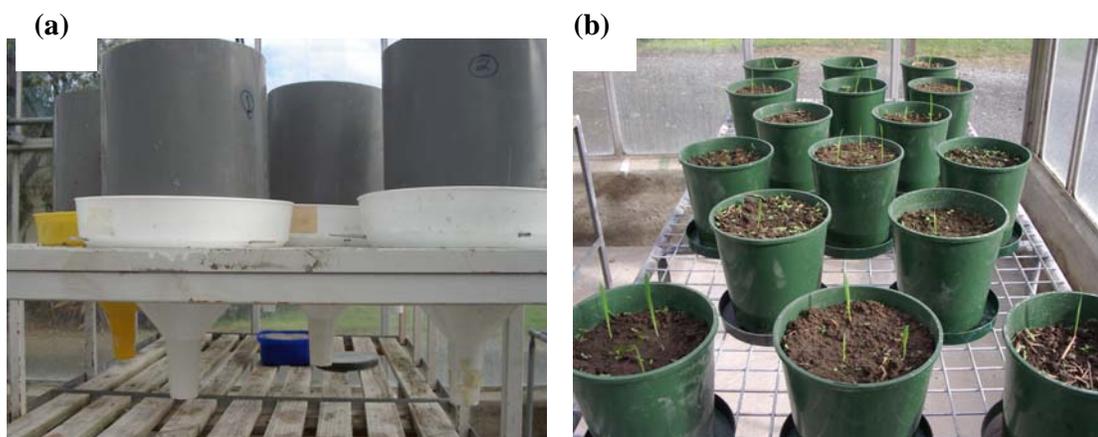
#### **3.3.2 Nitrogen release**

A variation of the leaching incubation method proposed by Stanford and Smith (1972), illustrated in Figure 3.3a, was used to determine N released from the soil by mineralisation. This involved the leaching of 16 of the packed cores (4 per treatment combination) every 14 days over 3 months (6 events) with one pore volume (1.5 L) of 0.01M CaCl<sub>2</sub>, between August 10 and October 19, 2007. The pore volume used was averaged for the 16 cores. The total volumes of leachate collected from all cores during each event were recorded. Sub-samples (100 ml) of leachate were kept for analysis and the rest was discarded. Air was pumped into the cores (Figure 3.4), after free drainage, to remove excess moisture and

prevent water-logging at the base. The concentrations of  $\text{NO}_3^-$ -N and  $\text{NH}_4^+$ -N in the leachate collected were measured using the FIA (Section 3.2.3).

### **3.3.3 Plant nitrogen uptake**

The remaining 16 packed soil cores (4 per treatment) were sown with oats (*Avena sativa* L. var. Hokonui); 3 plants per core (Figure 3.3b), on August 3, 2007. The sowing was done 14 days after cores were collected to allow the soil to settle and also to minimise any allelopathic growth inhibitions caused by the decomposing green manure. Plants were watered daily but no nutrient was supplied. The above ground plant biomass was harvested after 3 months, the same day leaching ended and the soil cores sampled. Plants were oven-dried at  $65^\circ\text{C}$  for dry matter determination and ground for C and N measurements as in 3.2.2. Soil in pots was sampled and mineral-N was extracted and determined as described in section 3.2.3.



**Figure 3.3** Glasshouse experiment: (a) soil cores used to determine N mineralisation and release by leaching; (b) pots used for assessing N availability for crop uptake.



**Figure 3.4** Air compressor system to remove excess moisture from soil cores after each leaching event.

### **3.4 Crop response**

To determine the effects of the treatment combinations on a subsequently sown arable crop in the field, all plots were uniformly cropped with spring wheat (*Triticum aestivum* L. var. Conquest). The wheat was drilled after the last lot of litterbags had been retrieved at the end of August 2007. Superphosphate was applied and cultivated in at 250 kg ha<sup>-1</sup> in all 16 plots before sowing to counter deficiencies that would have caused growth differences, especially since the lupin had been ploughed in three weeks before as green manure. In October, each of the 16 plots was split in half with one half getting two split applications of urea at 50 kg N ha<sup>-1</sup> four weeks apart, while the other half had no N applied. At maturity in February 2008, plant samples from all 32 subplots were collected for dry matter and grain yield determinations.

#### **3.4.1 Residual available soil nitrogen**

Five cores of soil were sampled at 0-15 cm depth and bulked from each of the 32 sub-plots at the time of wheat harvest, and then used to determine residual mineralisable nitrogen (RMN). The method used was adapted from that by Campbell *et al.* (1993). Two 25 g sub-samples of field moist soil were taken from each of the 32 samples. One set of sub-samples was immediately extracted with 80 ml of 2M KCl, filtered and frozen, while the second set of subsamples was incubated for four weeks at 25°C before extraction. The extracts were analysed for ammonium and nitrate using the FIA as described in section 3.2.3. The residual mineralisable-N (RMN) was determined as the difference between the NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N data from the two sets of extractions.

### 3.5 Statistical analysis

All data sets were statistically tested using the Genstat® 10.0 package. The methods used varied for different data sets as listed below.

1. Two-way analysis of variance (ANOVA) (in randomised block) was carried out for all balanced data ( $n = 16$ ). These included data collected from all 16 plots at individual dates and depths (for soil samples), such as mineralisable-N from soil extracts and leachates, accumulated mineralisable-N totals at all sampling dates, soil C and N, oat yields, oat biomass C and N, and wheat yields without the nitrogen factor.
2. For unbalanced data, where 8 of the 16 plots were sampled ( $n = 8$ ), particularly for lupin green manure production, two-sample  $t$ -test analyses were conducted on dry matter yield data for lupin and carryover barley, and on lignin, cellulose, C and N contents of straw/stubble remaining after decomposition.
3. Split-plot ANOVA was conducted on wheat yield data from the 32 subplots.
4. For data collected over time, but with unequal time intervals, particularly for the litterbag residue decomposition, the Restricted Maximum Likelihood (REML) procedure for repeated measures with unequal time points was used, sequentially adding terms to the fixed model.
5. Normal repeated measures ANOVA was carried out for leachate collected over time.
6. Regression and curve-fitting were done to determine rates where appropriate, with slopes tested for statistically significant differences using ANOVA.

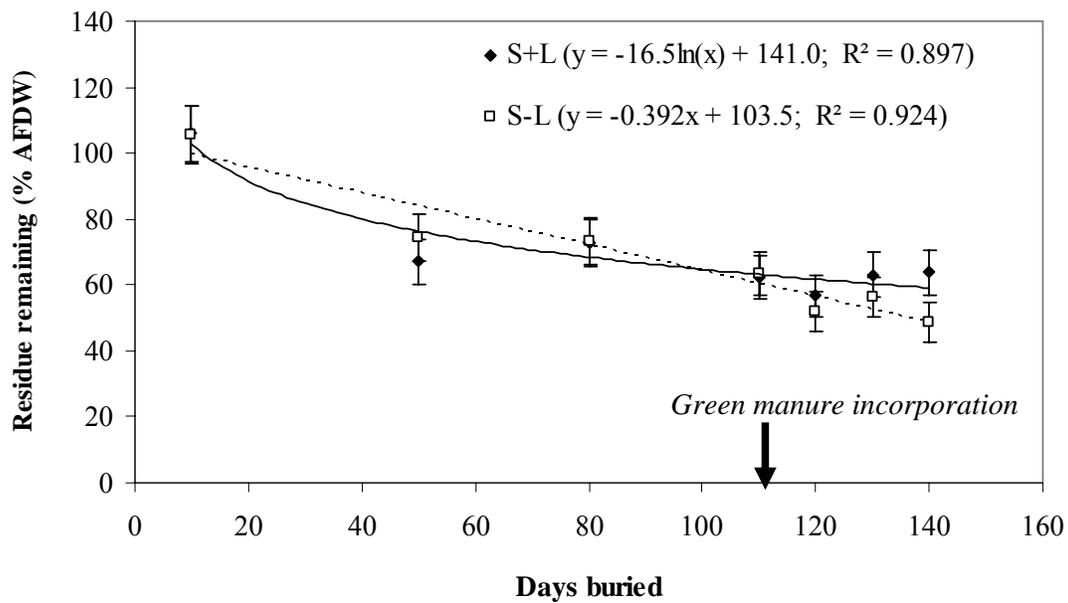
Data transformations were conducted where required before analysis of variances were carried out.

## Chapter 4. Results

### 4.1 Field experiment

#### 4.1.1 Straw/stubble decomposition

Decomposition was monitored in treatment combinations where straw/stubble was retained with either the inclusion (S+L) or exclusion of lupin (S-L). Due to the high variability of the ash-free dry weights (AFDW) of the residues, neither the slopes of the curves nor residues remaining at individual dates were statistically analysed. The variability was mainly caused by soil contamination of the residues, which could not be thoroughly removed by sieving. Hence, the dry weights of residue remaining for some of the plots were higher than the initial weights of straw/stubble placed in the litterbags, as is obvious in Figure 4.1 where the curves start at 105 % rather than 100 %.



**Figure 4.1** Amount of straw/stubble residue measured in litterbags retrieved from S+L and S-L plots over 140 days of decomposition. Values are means ( $n = 8$ ) of mass remaining expressed as ash-free dry weight (AFDW). Error bars represent standard error of means (SEM).

Straw/stubble decomposition in plots with lupin (S+L) proceeded in two distinct phases. Decomposition was rapid initially (40 % loss) until after 110 d when it slowed (4 % loss) (Figure 4.1). This was best described by a logarithmic decomposition rate of - 4.97 g of AFDW residue per day. At least 33 % of the initial 30 g of straw/stubble was lost in the first 50 days. The slow decomposition in the second phase resulted in 60 % of the residue (18 g) remaining after 140 d. In contrast, plots with no lupin (S-L) lost 0.12 g of AFDW straw/stubble residue steadily each day, following a linear decomposition pattern during the 140-day period. Of the initial 30 g of straw/stubble, 26 % was decomposed after 50 d with less than half (49 %) remaining after 140 d. Loss before green manure incorporation amounted to 37 % while that after 110 d was 12 %.

The analysis of the two distinct phases of decomposition before (10-80 d) and after (110-140 d) green manure incorporation in Figure 4.1 showed differences that were almost significant. Decomposition during the first phase (10-80 d) was rapid for straw/stubble in plots with lupin (S+L) ( $p = 0.08$ ), then became slower after 110 d ( $p = 0.09$ ) compared with those without lupin (S-L). The noticeable separation of the curves after 110 days coincided with the ploughing in of the green manure. However, the overall inclusion of lupin did not have a significant effect on residue decomposition during the period of measurement.

Changes in the chemical composition of straw/stubble showed that the differences in Figure 4.1 were closely related to differences in cellulose decomposition (Table 4.1). Lupin significantly increased ( $p < 0.05$ ) the decomposition of cellulose between 0 and 50 d with S+L and S-L having lost 12 % and 2 % of the initial cellulose, respectively. Decomposition was slowed to a halt between 60 and 100 d in both treatments until after 100 d when 13.4 % of cellulose in plots without lupin (S-L) was lost compared with the 6.3 % loss in plots with lupin (S+L). Extrapolation of the polynomial curves resulted in the disappearance of cellulose after 198 and 224 d in S-L and S+L, respectively. On average, residues in plots with lupin contained 2.79 % less cellulose compared to those with lupin ( $p < 0.05$ ) mainly due to the initial rapid loss during the study period (Table 4.1).

**Table 4.1** Mean ( $n = 4$ ) amounts of cellulose measured in straw/stubble residues in S+L and S–L over 140 d decomposition.

Treatment	Cellulose	Cellulose	Cellulose	Cellulose	Significance	SED
	at 0 d (%)	at 50 d (%)	at 110 d (%)	at 140 d (%)		
S+L	100	89.2	89.9	86.7	*	<b>2.76</b>
S–L	100	97.2	100	91.1		

Note: SED indicates standard error of the differences of means.

\* Significant at  $p < 0.05$

Due to heavy soil contamination of the litterbag samples, cellulose as a percentage of the organic matter content (100% - Ash content) in straw/stubble was used rather than the percentage dry matter. This resulted in the underestimation of the amount of cellulose lost through decomposition. Hence, the total decomposition of cellulose did not correspond with the total mass loss of straw/stubble presented in Figure 4.1.

Lignin contents of residues in both treatment combinations (S+L, S–L) increased from 6 to 14 % over the 140-day decomposition, therefore, there were no significant differences in the means obtained (Table 4.2). Residue C/N in both treatments decreased from 80 to 56 and 55 for S+L and S–L, respectively, with the means for the 140 days being similar (Table 4.2). Lupin had no significant effect on either lignin or C/N ratios of the residues retrieved from the litterbags.

**Table 4.2** Average lignin, cellulose and C/N contents of straw/stubble residue determined in litterbags sampled throughout the 140 d study period.

Treatment	Lignin (% om)	Cellulose (% om)	C/N
S+L	14.5	38.8	52
S–L	14.6	41.6	52
Significance	NS	*	NS
SED	<b>0.20</b>	<b>1.22</b>	<b>1.8</b>

Note: SED indicates standard error of the differences of means.

\* Significant at  $p < 0.05$

### 4.1.2 Green manure production

Above ground dry matter yields of lupin and weeds including carryover barley, and their N contents from treatment combinations that included lupin green manure regardless of straw/stubble management, are shown in Table 4.3. Lupin dry matter production in plots with straw/stubble retained (S+L) were significantly ( $p<0.05$ ) lower by 839 kg/ha (27 %) compared with plots where burning was used (B+L), while the opposite trend was observed for carryover barley weeds. The dry matter yields of weeds other than barley from the B+L and S+L treatments were 84 and 107 kg/ha, respectively, and were not significantly different.

**Table 4.3** Above ground dry matter (DM) and nitrogen (N) determined in the lupin green manure crop and carryover barley weeds.

<b>Treatment</b>	<b>Lupin DM (kg/ha)</b>	<b>Carryover barley DM (kg/ha)</b>	<b>N in lupin (kg/ha)</b>	<b>N in barley (kg/ha)</b>
<b>B+L</b>	3083	669	80.1	14.9
<b>S+L</b>	2244	1390	60.7	28.4
<b>Significance</b>	*	**	**	**
<b>SED</b>	<b>302.0</b>	<b>206.2</b>	<b>4.91</b>	<b>3.41</b>

Note: SED indicates standard error of the differences of means.

\* Significant at  $p<0.05$

\*\* Significant at  $p<0.01$

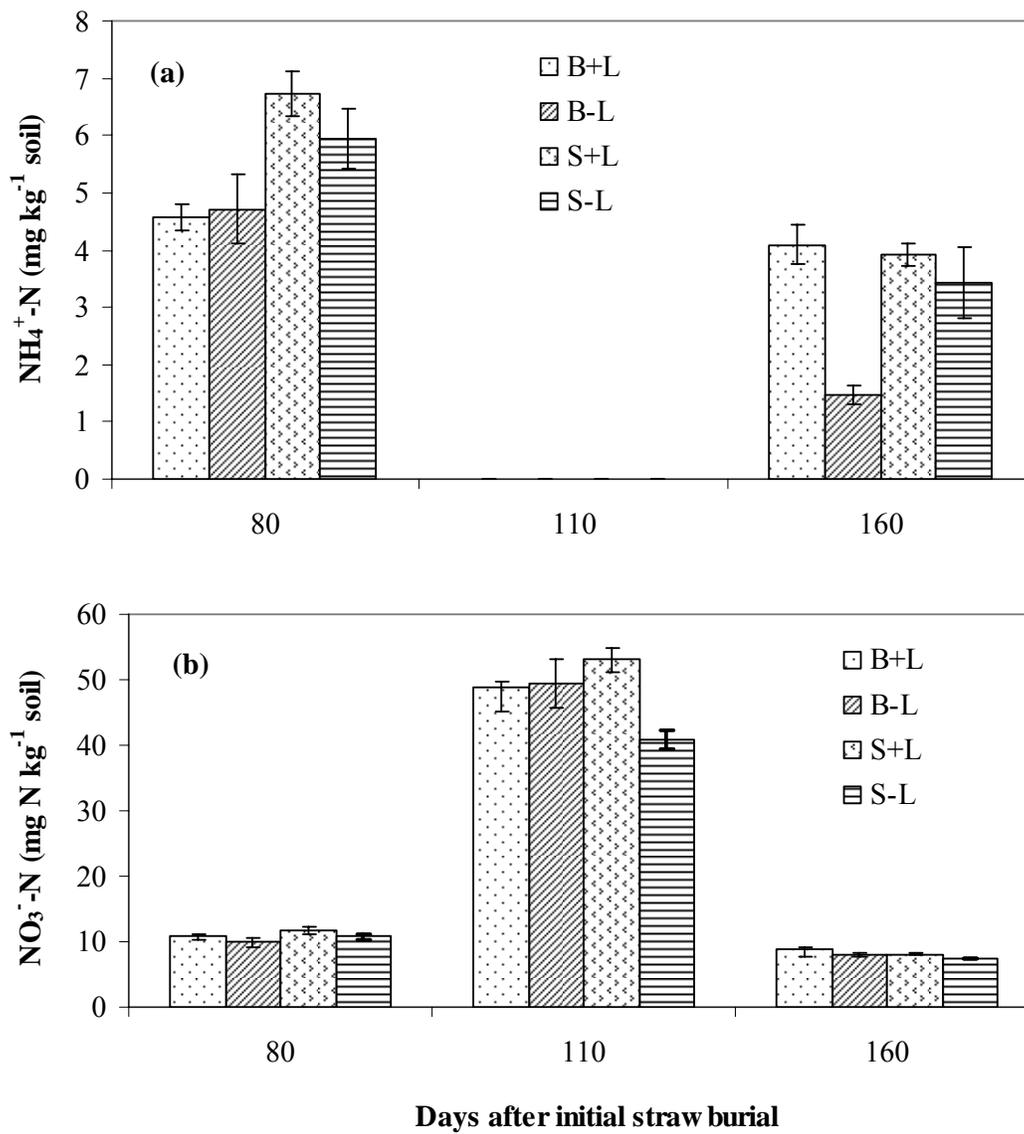
There were significant differences in the N contents of lupin and carryover barley between the different straw/stubble management treatments (Table 4.3). Lupin biomass from burned plots (B+L) contained 32 % more N compared to that from plots where the straw/stubble had been retained (S+L). In contrast, the N content of carryover barley on burned plots was only half that of treatments where the straw/stubble had been retained. The C/N ratio of the lupin biomass was 17.5 and 16.9 and for carryover barley was 19.7 and 21.6, on the B+L and S+L treatments, respectively (data not shown). However, these ratios were not significantly different ( $p>0.05$ ). Overall, total green manure dry matter incorporated in straw/stubble burned and retained plots were 3836 and 3741 kg/ha, with 80.4 % and 60.0% being comprised of lupin, respectively, but these values were not significantly different

( $p > 0.05$ ). Likewise, the total incorporation of green manure containing 95.0 and 89.2 kg N ha<sup>-1</sup> in burned and retained plots, respectively, were not significantly different ( $p > 0.05$ ).

### ***4.1.3 Nitrogen availability***

#### ***Ammonium-N***

Mineral-N measured in the soil during the decomposition period had no ammonium-N (NH<sub>4</sub><sup>+</sup>-N) at 110 d and therefore could not be statistically analysed (Figure 4.2a). Otherwise, amounts measured at the two depths (0–7.5, 7.5–15 cm) at 80 and 160 days were not significantly different for the 4 treatment combinations. Similarly, the cumulative totals of 10.7, 9.4, 8.7 and 6.2 mg N kg<sup>-1</sup> of soil from S+L, S-L, B+L, and B-L, treatments respectively, were not significantly different.



**Figure 4.2** Ammonium– (a) and nitrate–N (b) determined in soil sampled at 0-15 cm depth during the decomposition period. Error bars represent standard error of means (SEM).

### **Nitrate-N**

Nitrate-N ( $\text{NO}_3^-$ -N) in soil at 0–7.5 cm depth after 110 d showed significant differences between treatment combinations and have been presented as total mineral-N in Table 4.4 since there was no ammonium-N measured at 110 d. Nitrate-N in burned plots without lupin (B–L) was 30 % higher than those that had straw/stubble retained but without lupin (S–L), showing that burning significantly increased  $\text{NO}_3^-$ -N release. However, these differences were not observed in soil at 7.5–15 cm depth at 110 d. Neither were the nitrate-N values from soil at the two depths at 80 and 160 d significantly different. Figure 4.2b illustrates  $\text{NO}_3^-$ -N for the combined depths (0–15 cm). More nitrate-N was mineralised by 110 d than by the other 2 dates, with S+L and S–L treatments having the highest and lowest nitrate-N levels, respectively, albeit the levels were not significantly different ( $p>0.05$ ). More than a 70 % reduction in nitrate level occurred between 110 d and 160 d. However, there were no obvious differences in  $\text{NO}_3^-$ -N mineralisation between treatments. The mean concentrations from S+L, B+L, B–L and S–L treatments at 160 d of 12.9, 12.3, 12.0 and 10.6  $\text{mg N kg}^{-1}$  of soil, respectively, were not significantly different.

**Table 4.4** Total mineral-N measured in soil sampled from the four experimental treatments at various depths and times during the decomposition period.

Treatment	Total N at all depths & times ( $\text{mg N kg}^{-1}$ soil)	Total N at 0–7.5 cm at 110 d ( $\text{mg N kg}^{-1}$ soil)
B+L	77.1	27.2 <b>b</b>
B–L	73.7	32.8 <b>a</b>
S+L	83.4	28.2 <b>b</b>
S–L	68.5	22.0 <b>c</b>
Significance	NS	*
SED	8.08	1.13

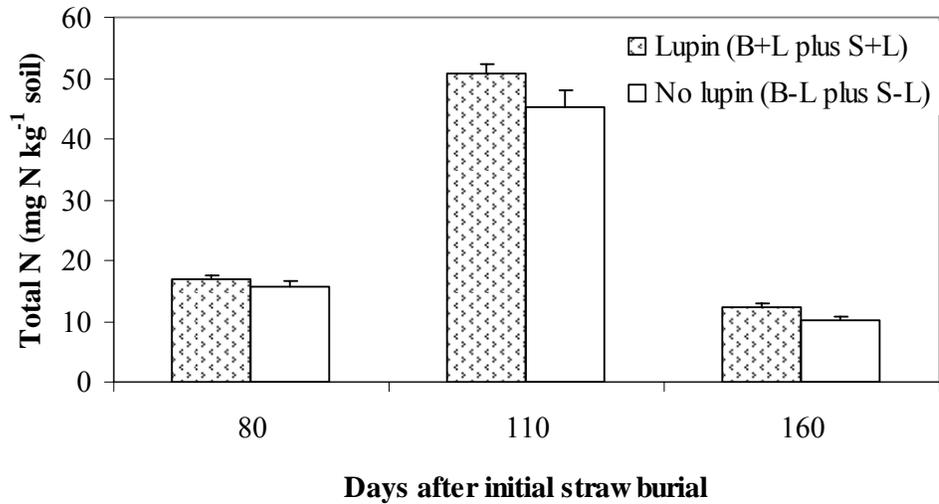
Note: SED indicates standard error of the differences of means. Means with the same letters were not different when separated using LSD values.

\* Significant at  $p<0.05$

### **Total mineral-N**

The REML analysis of total soil mineral-N ( $\text{NH}_4^+$ - and  $\text{NO}_3^-$ -N) during decomposition showed a mean increase of 64 % after 80 d and a 77 % reduction after 110 d. This trend was significant ( $p < 0.05$ ) with B-L and S-L having the most and least concentration changes, respectively. Differences in cumulative total mineral-N at all depths and times were not significant (Table 4.4). Similarly, total mineral-N at individual depths and times was not significantly different, except for soil sampled at 0–7.5 cm depth after 110 d, which was actually due to the significant differences in nitrate-N levels presented in Figure 4.3b.

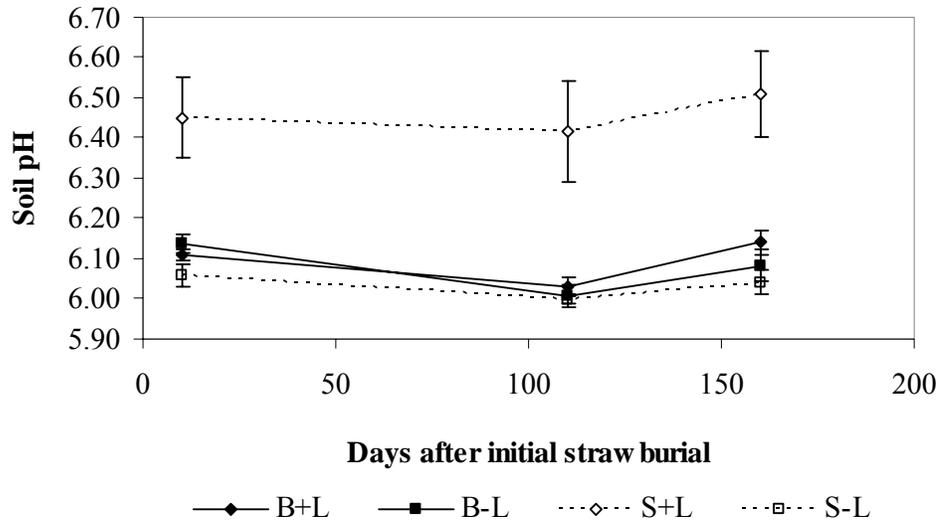
The overall influence of lupin on total mineral-N was significant ( $p < 0.01$ ) at the two soil depths at 80 d and at 160 d (0–15 cm depth) (Figure 4.3). At 80 d, mineral-N in the 0–7.5 cm depth was significantly lower ( $p < 0.01$ ) in plots with lupin (B+L plus S+L) compared to those without lupin (B-L plus S-L). The respective concentrations were 5.1 and 9.2 mg N  $\text{kg}^{-1}$  of soil. The opposite was true in the 7.5–15 cm depth at 80 d with concentrations of 11.5 and 6.4 mg N  $\text{kg}^{-1}$  of soil in plots with lupin and those without lupin, respectively, and their differences were also significant ( $p < 0.05$ ). At 160 d, plots with lupin had significantly ( $p < 0.05$ ) higher soil mineral-N concentrations than those without lupin with means of 12.4 and 10.2 mg N  $\text{kg}^{-1}$  of soil, respectively. Differences at 110 d were not significant. The C/N ratio of soil (0–15 cm depth) for all treatments remained at a mean of 12 throughout the trial period.



**Figure 4.3** Total mineral-N measured in plots with (B+L plus S+L) and without lupins (B-L plus S-L) during the 160 d since straw/stubble was initially incorporated. Error bars represent standard error of means (SEM).

#### **4.1.4 Soil pH**

Soil pH on plots with straw/stubble plus lupin (S+L) was significantly ( $p < 0.05$ ) higher than that on other treatment plots during decomposition with a mean of 6.46 on average over the three sampling times compared with the collective mean of 6.08 on the other treatments (Figure 4.4). All treatments had a slight drop in pH at 110 d before increasing, however, these changes were only slight with the mean for all treatment combinations being less than 0.1 unit. The magnitude of increase and decreases at 10 d from the initial pH of 6.23 were similar and ranged from 0.1 to 0.2 units.



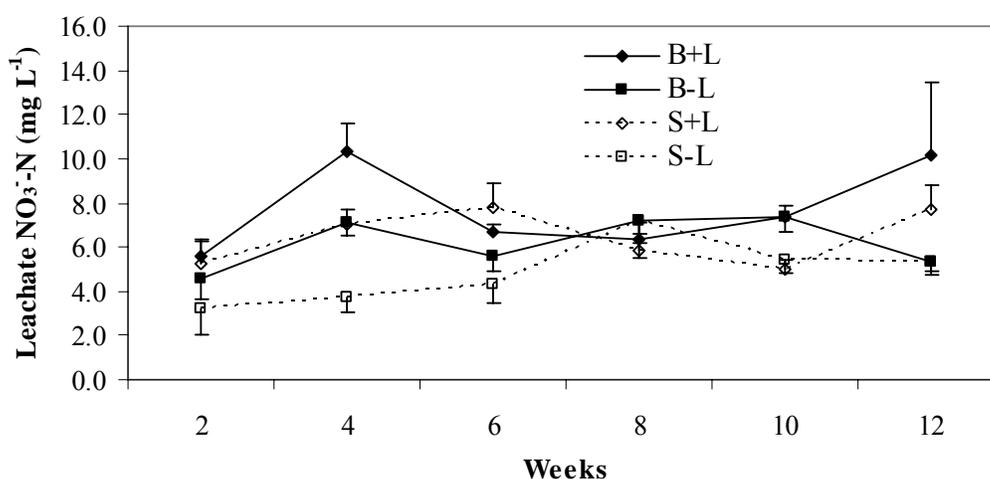
**Figure 4.4** Soil pH measured during the straw/stubble decomposition period between 10 and 160 d. Error bars represent standard errors of means (SEM).

## 4.2 Glasshouse experiment

### 4.2.1 Leachate ammonium- and nitrate-N

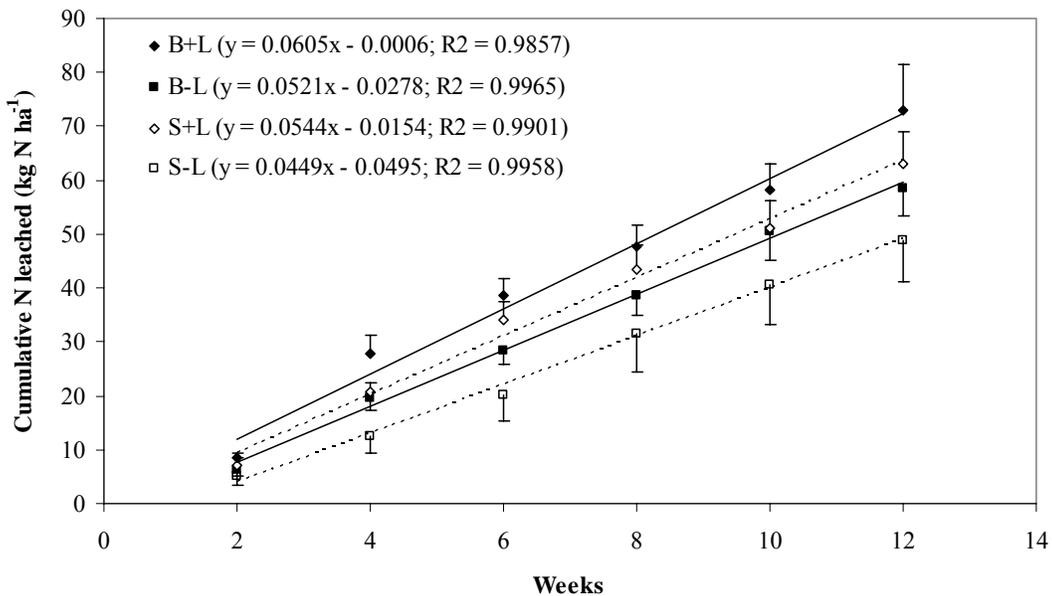
The concentrations of ammonium-N in leachate collected during all leaching events were negligible ( $<0.2 \text{ mg N L}^{-1}$ ) except for the first event. The concentrations were 0.7, 0.5, 0.3 and  $0.3 \text{ mg N L}^{-1}$  measured in S-L, B+L, B-L and S+L treatments, respectively, and were not significantly different ( $p>0.05$ ).

Nitrate-N concentrations fluctuated throughout the 12 weeks (Figure 4.5) and were highly variable. Differences noted at individual events were not significant ( $p>0.05$ ), nor were the cumulative totals of 46.5, 38.5, 37.2 and  $29.2 \text{ mg N L}^{-1}$  for B+L, S+L, B-L and S-L treatments, respectively. However, nitrate concentrations in leachate collected after 4 weeks from treatments where straw/stubble was burned (B+L plus B-L or B±L hereon) were almost significantly higher ( $p=0.07$ ) than those with straw/stubble retained (S+L plus S-L or S±L). Likewise, the overall incorporation of lupin (B+L plus S+L) produced an almost significant increase ( $p=0.08$ ) in the amount of nitrate-N leached after 4 weeks, compared with treatments without lupin (B-L plus S-L).



**Figure 4.5** Nitrate-N measured in leachate collected during the 12 weeks. Error bars represent standard error of means (SEM).

No obvious trends or significant differences were found in the total mineralisable-N released over 12 weeks from the 4 treatment combinations when subjected to repeated measures analysis. Figure 4.6 shows the cumulative mineralisable-N measured over the 12-week period. Amounts released from treatment combinations with burn and lupin (B+L) were high, followed by straw/stubble retained with lupin (S+L) and burn without lupin (B-L) with straw/stubble retained without lupin (S-L) the lowest. However, the slopes were not significantly different, nor were the cumulative total mineralisable-N measured after 12 weeks ( $p>0.05$ ,  $sed = 17.1$ ) due to high variability between treatments and replicates. The cumulative totals from B+L, S+L, B-L and S-L were 72.9, 63.0, 58.6 and 48.9  $\text{kg N ha}^{-1}$ , respectively.



**Figure 4.6** Cumulative total N measured in leachate collected fortnightly for 12 weeks between August 10 and October 19, 2007 from the 4 treatment combinations. Error bars represent standard errors of means (SEM).

### 4.2.2 Plant N availability

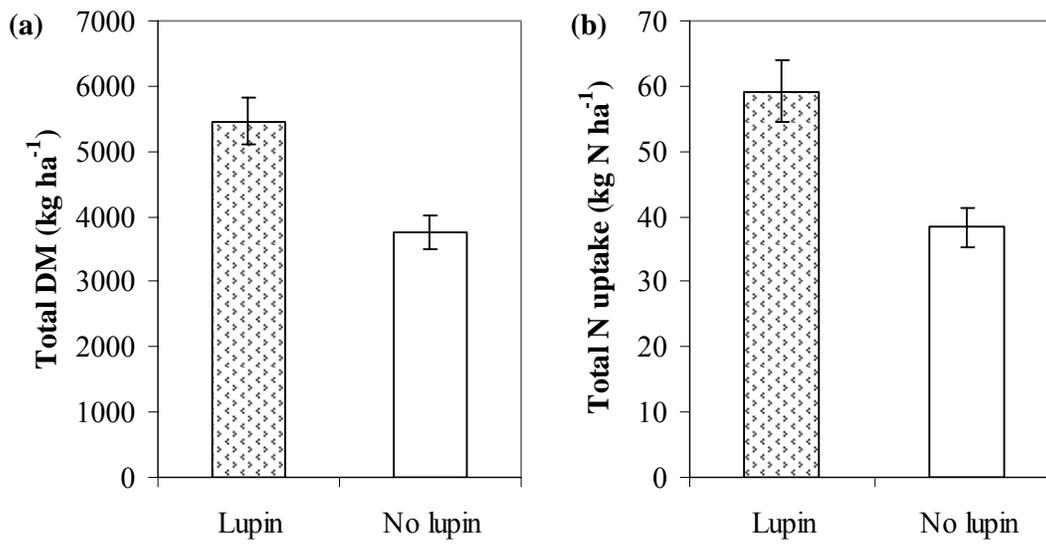
Above ground dry matter yield of oats, along with herbage N content and C/N values, are presented in Table 4.5. Oats in burn with lupin plots (B+L) gave the highest dry matter yield and N uptake, the amounts being twice those on the S–L treatment, although the values were not significantly different ( $p>0.05$ ). The N uptake in oats accounted for 88, 67, 79 and 70 % of mineralisable-N measured in the leachate for B+L, B–L, S+L and S–L, respectively. Mineralisable-N not taken up by oats was 8.6, 19.4, 13.2 and 14.2 kg N ha<sup>-1</sup> in the same order. The C/N of oats for the treatments was not significantly different.

**Table 4.5** Above ground dry matter yield, nitrogen uptake and C/N values determined in oats grown in pots following green manuring.

Treatment	Dry matter (kg ha <sup>-1</sup> )	N uptake (kg N ha <sup>-1</sup> )	C/N
B+L	6075	64.3	40.8
B–L	4459	39.2	48.9
S+L	4852	49.8	39.7
S–L	3039	34.7	36.8
Significance	NS	NS	NS
SED	857.9	12.02	4.19

Note: SED indicates standard error of the differences of means.

When the two treatment factors were analysed separately, significant differences ( $p<0.05$ ) were apparent (Figure 4.7). The overall inclusion of lupin green manure (B+L plus S+L) significantly increased oat dry matter yield by 1714 kg ha<sup>-1</sup>. Similarly, total N uptake in oats from treatments with lupin green manure (B+L plus S+L) was significantly higher ( $p<0.05$ ) than those without lupin (B–L plus S–L).



**Figure 4.7** Total above ground dry matter (a) and N uptake (b) of oats measured in lupin and no lupin treatments in the presence and absence of straw/stubble. Error bars represent standard errors of means (SEM).

Mineral-N measured in soil at the time of harvesting oats was not significantly different between the four treatment combinations. The values were 3.23, 5.13, 5.16 and 7.11 mg N kg<sup>-1</sup> from treatments B+L, B-L, S+L and S-L, respectively. Treatment effects were more obvious when nitrate-N was analysed. Straw/stubble retention (S±L) significantly increased (p<0.01) nitrate-N retention in soil while the inclusion of lupin (B+L plus S+L) significantly increased (p=0.01) its release, resulting in low amounts remaining in the soil at oats harvest. The amounts of nitrate-N were 3.44 and 1.89 mg N kg<sup>-1</sup> of soil for S±L and B±L, respectively, and 2.14 and 3.19 mg N kg<sup>-1</sup> of soil for B+L plus S+L and B-L plus S-L, respectively.

## 4.3 Crop response

### 4.3.1 Yield

The main treatment combinations had no significant effects on the total above ground biomass and grain yields of the succeeding wheat crop (Table 4.6). Although N application consistently increased yields, its effect was not significant on either dry matter or grain yield components. Plots with burn and lupin (B+L) gave the highest dry matter and grain yields from both the plus and minus fertiliser-N subplots, while burn plots without lupin (B-L) yielded the lowest. No significant interactions were detected.

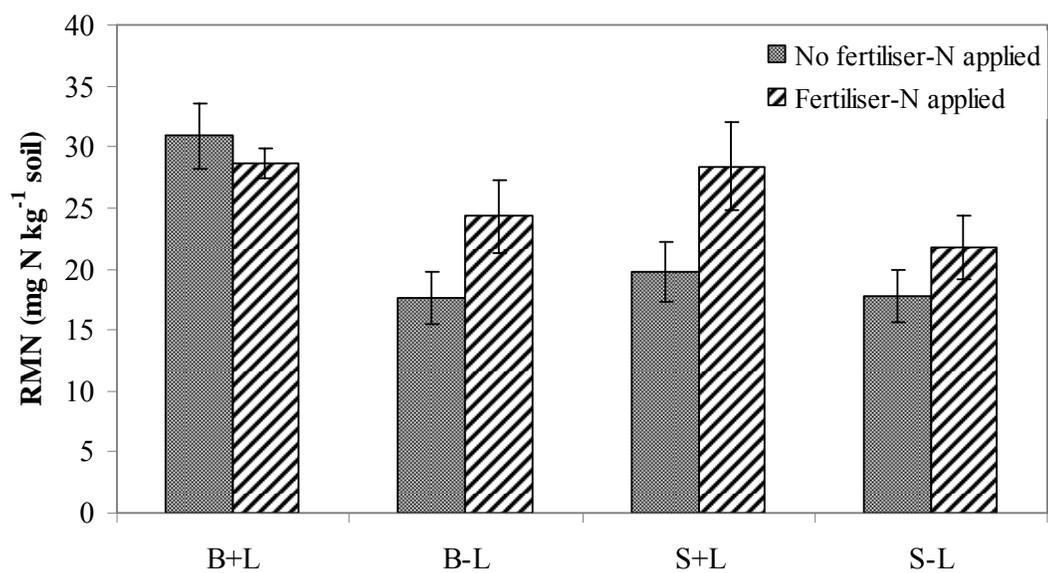
**Table 4.6** Total above ground dry matter and grain yields determined for the succeeding wheat grain crop over the 2007-08 season.

Treatment	Total dry matter (kg/ha)		Grain yield (kg/ha)	
	No N applied	N applied	No N applied	N applied
B+L	8268	8806	3756	3956
B-L	7262	7783	3108	3420
S+L	7505	7891	3276	3324
S-L	7504	8118	3291	3753
Significance	NS		NS	
SED	715.8		393.6	

Note: SED indicates standard error of the differences of means.

### 4.3.2 Residual mineralisable-N

Concentrations of ammonium-N were very low and are not reported here. The residual mineralisable nitrate-N (RMN) values measured in all 32 subplots were not significantly different ( $p > 0.05$ ,  $sed = 8.67$ ), even though plots where fertiliser-N was applied were generally higher than where no fertiliser-N had been added (Figure 4.8). The RMN in the B+L treatment with and without fertiliser-N addition were 28.6 and 30.9 mg N kg<sup>-1</sup> of soil, respectively. Nitrate-N released in the subplots without N application in the other 3 treatments was half that of B+L. The concentrations of RMN in the subplots with fertiliser-N in the 4 treatment combinations were similar.



**Figure 4.8** Residual mineralisable-N (RMN) measured in soil collected from all plots with and without N application. Error bars represent standard error of means (SEM).

## 4.4 Summary of results

- The inclusion of lupin green manure (S+L) resulted in an apparent increase in straw/stubble decomposition in the first growth phase, then reduction after green manure incorporation. This was best described by a logarithmic decomposition rate of  $-4.97$  g of residue AFDW day<sup>-1</sup>. Straw/stubble without lupin (S-L) decomposed linearly at  $-0.12$  g of residue AFDW day<sup>-1</sup>. However, the effects were not significant.
- Lupin green manure (S+L) significantly increased cellulose decomposition in the first 50 d then caused the decomposition to be slower than in straw/stubble without lupin (S-L) after green manuring at 110 d.
- Straw/stubble retention resulted in a significant 27 % reduction in lupin dry matter yield with a corresponding N content decrease. This was accompanied by a 50 % increase in weed dry matter yield, which resulted in the total green manure biomass and N incorporated not being significantly different.
- Nitrate was the dominant form of mineral-N in the soil sampled during decomposition. Amounts in the 0–7.5 cm depth were low in treatments where straw/stubble was retained and green manure growth was active, indicating immobilisation and plant uptake.
- Soil pH was stable during the experiment. The S+L treatment had a significantly higher ( $p < 0.05$ ) pH throughout the period compared to the pH values on the other treatments.
- Mineral-N release and uptake by oats, and dry matter yield were not significantly different on all treatments. The two methods used gave similar mineralisable-N results.
- Overall inclusion of lupin green manure significantly increased N available to plants, consequently increasing dry matter yield of oats.
- Dry matter production of wheat sowed in the field was increased by fertiliser-N application. Residual mineralisable-N in the B+L treatment was high but not significantly different.

## Chapter 5. Discussion

### 5.1 Straw/stubble decomposition

#### 5.1.1 Litter decomposition

Barley straw decomposition is reportedly a rapid process compared to the decomposition of other cereal straws (Smith and Peckenpaugh 1986; Summerell and Burgess 1989). The 33 % and 26 % loss of initial barley straw/stubble in plots with (S+L) and without lupin (S-L), respectively, in the first 50 d (Figure 4.1) were comparable with those reported elsewhere (Cookson *et al.* 1998; Beare *et al.* 2002; Curtin and Fraser 2003) for similar studies near Lincoln University, New Zealand, and at the Askov Experimental Station in Denmark (Christensen 1986). At least half the initial amount of straw/stubble had decomposed after 140 d, with 60 % and 49 % remaining in plots with and without lupin treatments, respectively.

The linear decomposition rate of residue in plots without lupin (S-L) at 0.39 % d<sup>-1</sup> was higher than the rate of 0.26 % d<sup>-1</sup> reported by Beare *et al.* (2002) and that of 0.07 % d<sup>-1</sup> reported by Christensen (1986). This was reasonable, however, given the burial of litterbags in the present study was in early autumn when air temperatures ranged from 10 to 22°C as opposed to late autumn when temperatures below 10°C reduce the speed of decomposition (Beare *et al.* 2002). With the high rate of straw/stubble decomposition in this study, the time of disappearance of the straw/stubble in the plots without lupin was expected to be sooner than those in other studies (e.g. (Christensen 1986; Smith and Peckenpaugh 1986; Beare *et al.* 2002; Curtin and Fraser 2003).

Unlike the steady decomposition of straw/stubble without lupin, decomposition in plots with lupin (S+L) proceeded in two phases with an initial rapid loss (40 %) followed by a slower (4 %) loss of residue mass. Cookson *et al.* (2002) and Curtin and Fraser (2003) reported a similar 2-phase decomposition with a rapid initial loss of the residue labile fraction, followed by a slower loss of the recalcitrant fraction. Microbial products synthesised during the initial flush were found to protect the surface of straw substrates and impede enzymatic hydrolysis, further slowing decomposition (Murayama 1984). The almost significant difference in straw/stubble mass loss noted before ( $p=0.08$ ) and after

( $p=0.09$ ) 110 d suggested that lupin green manure had some influence on the decomposition in the two phases. Lupin green manure appeared to increase decomposition during the growth period, then slowed decomposition after being ploughed in albeit the data failed to read significance. The increased availability of mineral-N due to contributions by lupin  $N_2$  fixation (Evans et al. 1989; Heenan 1995; Fowler et al. 2004) would have led to the increased decomposition while the ploughing in of green manure reduced decomposition of straw/stubble due to the addition of fresh organic matter (Kumar and Goh 2000).

The differences in straw/stubble mass loss from the litterbags earlier were closely related to the loss of cellulose from residues in the two treatment combinations. The three stages of cellulose decomposition were from 0 to 50 d when the 12 % loss in straw/stubble with lupin (S+L) was greater than the 2 % in straw/stubble without (S-L); followed by a halt during 60 – 100 d; and finally when decomposition after 110 d in S-L (13.4 % loss) was faster than in S+L (6.3 % loss). The initial rapid loss of cellulose supported the first phase in straw/stubble decomposition, which was similar to the 10 % loss in barley straw reported by Henriksen and Breland (1999). The introduction of additional cellulose with the green manure incorporation resulted in reduced decomposition of straw/stubble, thus explaining the slow loss of cellulose after 110 d compared to treatment S-L which had no green manure. The halt between these two phases coincided with decreasing temperatures between mid May and July 2007, which slowed decomposition by reducing efficiency of soil microbial biomass (Smith et al. 1993; Henriksen and Breland 1999). The full effect of lupin green manure after ploughing could not be determined due to the removal of all litterbags. Hence, the significantly ( $p>0.05$ ) low cellulose content of straw/stubble residue remaining during the 140 d due to the overall inclusion of lupin (Table 4.2) was mainly due to the high loss during the first phase.

The mass and cellulose loss of straw/stubble in this study were rapid and were expected to end sooner than the losses reported in other studies (e.g. (Christensen 1986; Henriksen and Breland 1999; Beare et al. 2002)). The changes in lignin and C/N during decomposition were the same in both treatment combinations, and these were not influenced by lupin. The increase in lignin content (6 % to 14 %) was consistent with reports by Summerell and Burgess (1989), and was mostly due to residues losing cellulose and hemicellulose and becoming more recalcitrant over time.

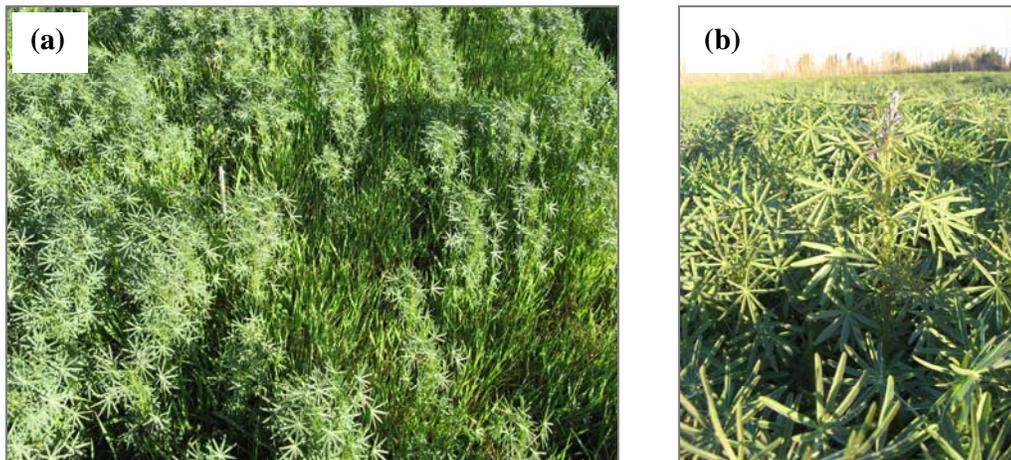
Due to the high variability of the amount of straw remaining in litterbags, differences in decomposition rates were not statistically tested. In hindsight, the method used could have been modified by first drying then sieving the samples to remove fine soil that was attached to residues before grinding, or else washing the residues before drying. However, this would have further disintegrated most of the finer decomposed residues and created other artefacts. In addition, the two sets of ashing of residues done could have been increased to three to further reduce the variability in mass loss of straw/stubble.

### **5.1.2 Green manure production**

The retention of straw/stubble significantly reduced lupin dry matter (DM) production, an observation also noticed in 5 of the 13 years of study conducted by Heenan *et al.* (2000). Lupin growth in plots with straw/stubble retained was restricted by the presence of weeds, especially carryover barley. Plots with straw/stubble retained were dominated by carryover barley in contrast to burned plots (Figure 5.1) resulting in a reduced emergence of lupin in the former plots (Heenan *et al.* 2000). This led to a significant ( $p < 0.05$ ) reduction of lupin dry matter production by 839 kg/ha in plots with straw/stubble retained (S+L) compared to plots where burning was used (B+L). Straw/stubble burning was effective in reducing weed occurrence and resulted in good establishment of the lupins as seen in other studies (Staniforth 1982; Heenan *et al.* 2000; FAR 2006).

The 3083 and 2244 kg DM ha<sup>-1</sup> yields of lupin and corresponding N uptake of 80 and 61 kg ha<sup>-1</sup> in B+L and S+L treatments were comparable with those obtained by other workers (Janson 1984; (McLenaghan *et al.* 1996; Francis *et al.* 1998; Fowler *et al.* 2004; Cherr *et al.* 2006). The difference in lupin dry matter yields between the B+L and S+L treatments disappeared when total green manure ultimately turned under was considered, which were 3836 and 3741 kg DM ha<sup>-1</sup>, respectively. The reduced lupin DM yield in S+L treatment was compensated for by the carryover barley in these treatments. Lupin compositions of the total green manure incorporated were 80.4 % and 60 % for the straw/stubble burned and retained treatments, respectively.

The differences in lupin N content were reasonable given the low aboveground dry matter yield. The high lupin dry matter yield in burned plots resulted in a 32 % higher N content compared to plots where straw/stubble were retained. The reduction in N uptake of lupin growing with straw/stubble retained was compensated for by the significantly higher barley N uptake compared to lupin in burned plots. Barley N uptake in both treatments fell within the range for non-legumes summarised by Thorup-Kristensen *et al.* (2003). As with the dry matter yields, the total N incorporated in the green manure in B+L (95 kg N ha<sup>-1</sup>) and S+L (89 kg N ha<sup>-1</sup>) treatments was not significantly different.



**Figure 5.1** Lupins at 100 d showing the dominance of carryover barley weeds in plots with straw/stubble retained (a) and with sparse weeds in burned plots (b).

The C:N ratios of lupins and barley from two treatment combinations were not significantly different. The mean of 17 for lupins was similar to that reported by Fowler *et al.* (2004). The C/N for both lupin (17) and barley (21) from both treatment combinations fell within the green manure crops C/N ranges of other studies reviewed by Thorup-Kristensen *et al.* (2003). Net mineralisation would probably have occurred given that these values were below 25 (Kumar and Goh 2000).

### 5.1.3 Nitrogen availability

The low concentrations of ammonium-N in the soil during the decomposition indicated gross nitrification, even at low temperatures, as was observed by Magid *et al.* (2001) and Cookson *et al.* (2002) (Figure 4.2a). The absence of ammonium-N in soil sampled at 110 d was due to both low temperatures during June (0.2 – 11.6 °C) and July (2.2 – 10.5°C) (Figure 3.1), which slowed mineralisation of organic N (Kumar and Goh 2000), plus the complete nitrification of all mineralised ammonium-N (Magid *et al.* 2001). In contrast, nitrate-N concentration during this period was higher than those at 80 and 160 d (Figure 4.2b). The nitrate-N concentrations measured ranged from 32.8 to 22.0 mg N kg<sup>-1</sup> of soil in decreasing order: B–L > S+L = B+L > S–L. Nitrogen released during the burn, mostly from residues and dead microbial biomass (Biederbeck *et al.* 1980), was not used by plants as it was in plots with lupin green manure, nor was it immobilised by straw/stubble decomposition in the 0–7.5 cm soil depth. The inclusion of lupin in S+L and B+L treatments reduced nitrate-N concentrations through plant uptake by the lupins (Fowler *et al.* 2004). However, the supply of fixed N by lupin in the two treatments compensated the reductions that were otherwise observed in the S–L treatment. This effect was more obvious near the soil surface due to the depth at which straw/stubble was buried, ash on the soil surface after the burn, and the length of plant roots (Curtin and Fraser 2003). The retention of straw/stubble compared to burning immobilised N resulting in its reduced availability for plant uptake evident in the 0–7.5 cm depth samples (Christensen 1986; Beri *et al.* 1995; Bhogal *et al.* 1997).

Apart from low temperatures slowing the mineralisation of organic-N, the accumulation of mineral-N at 110 d also coincided with lupin maturity and a high biomass related to high N<sub>2</sub> fixation (Evans *et al.* 1989). Low concentrations of mineral-N after 80 d indicated crop uptake while high rainfall (137 mm) during June and July (Figure 3.1) led to leaching of nitrate-N resulting in the 77 % reduction of total soil mineral-N at 160 d. The variations between treatments in concentrations of mineral-N over time and depths were not significantly different, nor were the amounts of total mineral-N measured in soil during the 160 d. It was obvious that the four replicates used in this study may not have been sufficient to reduce variations in the collected data, resulting in treatment combinations having similar effects.

The inclusion of lupin (B+L plus S+L) significantly reduced mineral-N by 44 % at 0–7.5 cm soil depth after 80 d compared to the exclusion of lupin (B–L plus S–L), confirming N-uptake during early growth of green manure. The application of herbicide in the latter treatments also reduced plant uptake of mineral N thus contributing to the higher soil N content. The increase in mineral-N in soil at 7.5–15 cm depth compared to that at 0–7.5 cm indicated the accumulation of N either not taken up by plants or leached. This difference was not observed in the combined depths of 0–15 cm (Figure 4.3) due to totals being similar. Similarly, the total mineral-N contents at 110 d were not significantly different. However, the significantly high mineral N content at 160 d due to the mineralisation of lupin green manure incorporated compared to treatments without lupin emphasised the importance of including a legume green manure in crop rotations.

#### **5.1.4 Soil pH**

The changes over time in soil pH for the individual treatment combinations were not significant (Figure 4.4). Soil pH in straw/stubble retention and lupin green manure combination (S+L) was 0.4 units higher than the other treatments throughout the 224 d study period. This is thought to have been due to the decarboxylation of organic anions released during residue decomposition (Singh and Rengel 2007). However, this difference could have also arisen from the increased incorporation of organic matter diluting the amount of soil material in the pH measurements done.

## 5.2 Glasshouse experiment

### 5.2.1 Mineralisable-N release

The objective of the incubation/leaching glasshouse experiment was to determine the total amount of mineral-N that could be released after green manure incorporation. All treatments had significant amounts of ammonium-N ( $>0.2 \text{ mg N L}^{-1}$ ) only during the first leaching event and these concentrations ( $0.3 - 0.7 \text{ mg N L}^{-1}$ ) were similar to those measured by Fowler *et al.* (2004). Cultivation carried out before soil core collection and transfer into the glasshouse would have contributed to the disappearance of ammonium-N either through volatilisation or oxidisation into nitrate-N. Previous studies have shown the dominance of nitrate-N in leachate (McLenaghan *et al.* 1996; Fowler *et al.* 2004), which was found to result from the increased mineralisation of N in crop residues and soil organic matter following soil cultivation disturbances (Shepherd *et al.* 1993).

Although nitrate-N released from the B+L treatment was higher than the rest of the treatments particularly at weeks 4 and 12 with concentration of  $10.0 \text{ mg N L}^{-1}$  measured (Figure 4.5), the high variability in the concentrations led to the differences being non-significant. Similarly, burning of straw/stubble resulted in increased N release from the residues compared with the retention of straw/stubble as seen in the study done by Biederbeck *et al.* (1980) though the differences in the present study were almost significant. The consistently low amounts of nitrate-N released from straw/stubble retained without lupin (S-L) throughout the leaching periods indicated immobilisation of N resulting in 17 to 37 % reduction in the cumulative nitrate-N leached. This was consistent with studies conducted elsewhere under similar conditions, and especially during winter (Nicholson *et al.* 1997). The mineralisation of up to  $80 \text{ kg N ha}^{-1}$  in the lupin green manure incorporated led to an almost significantly high nitrate-N release in treatments with lupin (B+L plus S+L) than those without lupin (B-L plus S-L) as previously observed by Fowler *et al.* (2004). With mineral-N totals being comparable with those obtained by Francis (1995) for leguminous grain crops ( $75 \text{ kg N ha}^{-1}$ ), the inclusion of lupin green manure seemed to increase the release of mineral-N.

### **5.2.2 Plant nitrogen uptake**

The second method used to determine mineral N released after green manure incorporation was by measuring the actual uptake in plants in a concurrent pot trial. The uptake of mineral N by oats in pots (Table 4.5), accounted for 88, 79, 66 and 71 % of the total released mineral N measured in leachate from the respective treatment combinations. Though the treatments were not significantly different, conditions in treatments with straw/stubble burn and lupin (B+L) seemed to encourage mineral-N release and uptake by oats, resulting in the high dry matter (DM) yield of 6.1 t ha<sup>-1</sup> (Table 4.5). In comparison, oats in treatments with straw/stubble and no lupin (B-L) had low N uptake with 19.4 kg N ha<sup>-1</sup> released not accounted for and hence, gave a low DM yield of 4.4 t ha<sup>-1</sup>. The overall retention of straw/stubble (S±L) that significantly increased mineral N immobilised in the soil, reduced its availability for plant uptake. In contrast, the incorporation of lupin (B+L plus S+L) that gave significantly high soil mineral N remaining in pots meant the release of N from the green manure for oat uptake was slower than the growth of oats. The yields obtained were comparable with those obtained in a study by Fowler *et al.* (2004) (4.2 t oat DM ha<sup>-1</sup> at 150 d after sowing) and those predicted by Hughes *et al.* (1984) for forage oats (~0.5–1.9 t DM ha<sup>-1</sup>) harvested 60 days after sowing in various sites in New Zealand. The differences in yields can be explained by the fact that this study was conducted in a glasshouse with higher temperatures and in pots compared to the lysimeter and field trials conducted during winter by the other researchers.

Although yield differences were not significant on average over burn and no burn treatments, the inclusion of lupin green manure significantly increased N uptake and oat DM yield by 55 % and 46 %, respectively, compared to the exclusion of lupin (Figure 4.7). This further supports the benefits of including a legume green manure for improving N supply and availability. On the other hand, the retention of straw/stubble was effective at immobilising and retaining N in the soil. Residual mineral-N in pots at harvest accounted for some of the N released during leaching that was not taken up by oats.

More than 70 % of the mineral N measured by the leaching incubation method was taken up by oats in the pot experiment. Hence, the results from the two methods of measuring mineralisable-N used in this study showed they were comparable.

### 5.3 Crop response

To confirm the differences between treatments observed in the glasshouse, the wheat crop was grown following green manuring in field conditions three weeks after oats were sown. As with oats in the glasshouse trial, there were no significant differences in the dry matter and grain yields from the four treatment combinations either with or without fertiliser-N application. Wheat yield in treatments with straw/stubble burned and lupin (B+L) was higher than the other treatments as was observed in oat dry matter yield, though these differences were not significant. Wheat grain yields were relatively low but comparable to those reported by Curtin and Fraser (2003) following cereal, and half that produced on ungrazed plots reported by Francis *et al.* (1998). The differences in wheat yields were reasonable given green manure followed ryegrass/clover crop (Francis *et al.* 1998) compared to spring barley used in this study. Furthermore, no irrigation and lower than average rainfall received during the growth period in this study (Figure 3.1) meant water availability was the major limiting factor. With irrigation, differences between the treatments presumably would have been greater.

The application of fertiliser-N generally increased yield, with the increases in DM and grain in plots where straw/stubble was retained without lupin (S–L) being the highest. Straw/stubble with lupin (S+L) was least influenced by fertiliser-N with 5 % and 1.5 % increase in DM and grain yields, respectively, resulting from fertiliser-N application. These increases were low compared to the 20 % reported by Dalal *et al.* (2007) from a similar study done in Australia, where fertiliser-N was applied at 75 kg N ha<sup>-1</sup> after straw incorporation compared to no fertiliser-N. The lack of sufficient soil moisture again limited crop uptake of fertiliser-N and ultimately affected grain yields. The lupin green manure used in this study seemed to have supplied enough N for both straw/stubble decomposition and crop growth, hence obscuring the effect of the fertiliser-N. Peoples *et al.* (2001) found that the amount of fixed N in soil after a grain legume like lupin was sufficient to cater for at least one subsequent non-legume crop. In contrast, the supply of fertiliser-N in this study would have not only supplied the much needed N for plant growth in plots without lupin (S–L), but also released N previously immobilised during straw/stubble decomposition, resulting in increased yield.

The initial flush of soil mineral N after the burning of straw/stubble seemed to have disappeared with both DM and grain yields in the B-L treatment being the lowest, however, the differences were not significant. This indicated nutrient limitations, particularly N, that would have been due to low gross mineralisation and microbial mass and activity (Biederbeck et al. 1980; Kumar and Goh 2002; Hoyle and Murphy 2006). The similarities in DM and grain yields meant the effects of burning were comparable with straw/stubble retention, which was also observed by Curtin and Fraser (2003).

### **5.3.1 Residual mineralisable-N**

Though not significant, the high yield from the B+L treatment was supported by the high amount of residual mineralisable-N (RMN) in both N- and no N-applied subplots (Figure 4.8). The low amount of RMN in treatments with straw/stubble retained indicated that some of the fertiliser-N applied was immobilised in the residues. Bhogal *et al.* (1997) reported immobilisation of up to 10 kg ha<sup>-1</sup> of spring-applied N by 7.5 t ha<sup>-1</sup> wheat straw incorporated in autumn, depending on extent of decomposition. Similarly, some of the fertiliser-N would have been immobilised reducing availability as mineral-N however, the actual amount could not be determined as bulk density measurements were not done. Yield in treatment, particularly where straw/stubble was retained with lupin (S+L), was increased by fertiliser-N, which reflected the influence of fertiliser-N on mineralisation. The release of N immobilised in straw/stubble decomposition and that released from green manure would have resulted in the increased residual mineral-N still available in the soil after wheat harvest. The inclusion of lupin seemed to improve the bioavailability of N, however, the yield differences were not significant. This was in agreement with Francis (1995) who found lupin maintained rather than increased the yield of the following wheat crop compared to oats and mustard, which reduced yields.

## Chapter 6. General Discussion & Conclusions

The general consensus that the incorporation of crop residues with wide C/N ratios like cereal straw immobilise N thus conserving it from loss could not be confirmed in this study. The retention of barley straw/stubble, compared to its burning, seemed to reduce the immediate availability of mineral-N to plants that resulted in non-significant reductions in dry matter yields of subsequent crops. The immobilisation of N in straw/stubble that resulted in low mineral-N contents was obvious in the 0–7.5 cm depth soil, showing the effect of straw/stubble in the depth it was buried. Consequently, crop N uptake in the presence of barley residues was reduced. However, oats and wheat biomass yields obtained in this study showed that the retention of straw/stubble had a similar effect as burning on crop production. The fact that straw/stubble application reduced N losses even though they were not accompanied by increased crop yields is consistent with other studies (e.g. Hobbs and Brown 1957). Yield increases often reported are from long-term studies and have been related to improved SOM and general fertility and not the increased retention of N. Hence, the effects of straw/stubble retention were not visible given the short-term nature of the present study.

This study showed that the ability of lupin green manure to alleviate the reduced availability of N in the presence of barley straw/stubble was only effective during its growth phase and not after it was ploughed in. The fixed N supplied by lupin increased the decomposition of the straw/stubble, especially cellulose, which was a contributor to the overall mass loss of the residue. Although lupin establishment and growth was restricted by straw/stubble incorporation, N fixation was optimised by the low mineral-N content. This was confirmed by the low N concentrations in the top 7.5 cm of soil during lupin green manure growth, indicating both plant uptake and immobilisation, whilst the N that was fixed by lupin accumulated in the 7.5–15 cm depth during that period. After being ploughed in, lupin green manure would have initially slowed straw/stubble decomposition as fresh organic C sources were introduced to the decomposer biomass before increasing decomposition as a result of gross mineralisation of the lupin with narrow C/N of 17. An extension of the period of measurement beyond 140 d was required to confirm further the effect of lupin on decomposition. Apart from that, more replicates were required and the

method for residue retrieval from litterbags needed to be improved to reduce the variability in weights of remaining residues observed in this study.

The burning of straw/stubble and lupin inclusion seemed to be the ideal combination for increased N availability and crop biomass production. Burning of straw/stubble had its advantages in that nutrients released in the ash and dead microbial biomass remaining after the burn would have been easily accessible to plants. Burning also reduced the occurrence of weeds, pests and diseases that reduce emergence and restrict growth, and resulted in the high population density of lupin that led to high DM yields. However, the release of nutrients after burning was short-lived without the inclusion of lupin as was shown by the low wheat yields obtained where burning without the legume was employed. The residual mineralisable-N present after the crops were harvested indicated a prolonged beneficial effect of lupin green manure incorporation. This, combined with lupin encouraging greater population of bacteria and fungal hyphae (microbial diversity) (Cookson et al. 1998), improving aggregate stability (Chan et al. 1994), and the overall contribution to SOM, could support continued benefits for crop production. This agreed with other workers who showed that the effects of lupin increased with time (Heenan 1995; Stark et al. 2006).

The leaching incubation and pot trial used in the glasshouse to determine N mineralisation and availability, although different, gave results that were comparable. The N uptake of oats in pots that accounted for up to 88 % of the N released by leaching, combined with residual mineral-N in pots after harvest, resulted in amounts of mineral-N similar to those obtained by leaching. Further, the consistent trends in biomass yields of oats in the pot and wheat in the field displayed the versatility of the pot trial. Not only can it be used to measure the potential mineralisable-N, but crop yield trends to determine differences in treatments, therefore reducing the need for a field trial. Given that oats were harvested two months earlier than wheat, the biomass yield differences in the corresponding treatments between the two crops would have been reduced if oats were allowed to reach maturity.

This study showed lupin green manure, that is also a catch crop and an organic source of N, had the potential to assist with the decomposition of residues with wide C:N ratios during its growth. This is useful in arable cropping systems that are dominated by cereal rotations and winter fallows. Legumes can be included in cereal rotations to help reduce cereal residues that are otherwise burned off, and to restore soil fertility in the same field.

Furthermore, long-term benefits of soil fertility improvement and maintenance, and reduced environmental pollution and degradation exist with the use of a legume green manure. However, the importance of synchronising N release and N use after a legume green manure is hereby emphasised to reduce loss, particularly after incorporation as was noted in the pot experiment in this study.

Further research on the influence of a legume green manure on the different phases of decomposition before and after its incorporations over a longer period of time is required. The differences in cellulose decomposition can be studied more closely to confirm the patterns that were observed in this study. Results can further determine the minimum time required for decomposition before a subsequent crop can be sown without significant yield reductions.

Herewith the main conclusions derived from this study:

- i. The retention of straw/stubble contributed to soil N retention only in the 0-7.5 cm depth and did not result either in crop yield increases or decreases when compared to straw/stubble burning;
- ii. The inclusion of lupin green manure significantly increased cellulose decomposition presumably through its contribution in supplying fixed N, which contributed to the mass loss observed during the growth period;
- iii. The beneficial effects of lupin green manure were not obvious in this study, although there was some evidence of it improving the availability of N for plant (oats) uptake resulting in higher biomass yield compared to its exclusion.

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