SHORT-TERM EFFECTS OF GRAMINACEOUS COVER CROPS ON AUTUMN SOIL MINERAL NITROGEN CYCLING IN WESTERN LOWER FRASER VALLEY SOILS

by

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ABSTRACT

Proper cover crop management practices in autumn can minimize NO_3^--N leaching. Three experiments to study the effect of cover crop management on autumn soil mineral N conservation were conducted in the 1991-92, 1992-93 and 1993-94 winter seasons on a silty clay loam Rego Humic Gleysol in the western Lower Fraser Valley, British Columbia, Canada. The study tested short-term effects of planting date, autumn soil mineral N content and type of cover crop on biomass production and N uptake, residual soil mineral N (0-60 cm layer), plant composition of various N fractions of autumn-planted spring species at winter-kill, retention of accumulated N by autumn-planted spring species after winter-kill, and the C/N ratio of cover crops. Treatments involved two planting dates (late August and September), two simulated autumn residual mineral N levels (0 and 100 kg N ha^{-1}) and types of cover crops. In the first two seasons, the cover crop treatments were spring barley (*Hordeum vulgare* L.) and winter rye (*Secale cereale* L.) plus fallow for comparison purposes. In the third season, planting date was omitted and six cover crop treatments tested were spring barley, spring wheat (*Triticum aestivum* L.), spring oat (*Avena sativa* L.), winter rye and annual ryegrass (*Lolium multiflorum* Lam.) including fallow.

Planting crops in August as compared to a month later increased biomass production by 56 to 135% and N uptake by 38 to 93% before winter leaching period. Large N uptake by cover crops that were planted in August was generally accompanied by significant reduction in soil mineral N (0-60 cm) from August to November.

August-planted spring species N at winter-kill was largely composed of the protein fraction (insoluble and soluble) which increased with N supply in autumn when the initial mineral N contents in 0-60 cm layer of soil were suboptimal (< 100 kg N ha^{-1}) but was not affected when soil mineral N content was 200 kg N ha^{-1} and more or when the cover crops were planted in

September. There were indications that August-planted spring species can retain some of the soluble protein N fraction in the winter-killed residues during winter. Maximum plant NO_3^--N content represented about 15% ($\sim$ 20 kg N ha^{-1}) of the total N in the plant when cover crops were planted in August and autumn soil mineral N content (0-60 cm) was about 200 kg N ha^{-1} or more. The proportion of NH_4^+-N averaged only 3%.

Spring species can be included in winter cropping systems in western Lower Fraser Valley. Spring species that were planted in August and winter-killed in late autumn showed greater potential to retain the N accumulated before winter-kill compared to the cover crops that were planted a month later. August-planted spring species increased soil mineral N (by 40 to 76%) in the 0-60 cm layer in spring relative to fallow plots while September-planted crops had little effect. It appears, spring species can play a significant role in autumn mineral N conservation by accumulating large amounts of autumn soil mineral N before winter leaching period, retaining it in winter-killed residues until spring and releasing the N in plant available form through decomposition and mineralization.

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Chapter 1: GENERAL INTRODUCTION

1-1. BACKGROUND

The western Fraser Valley (Fraser River delta) has one of the most productive agricultural lands in Canada. The region has the longest period of frost-free days in Canada (Luttmerding, 1981) and its temperate climate is generally characterized by warm rainy winters and relatively cool dry summers (Hare and Thomas, 1979). Long growing seasons, highly productive soils, and flat topography which allows for mechanization, installation of subsurface drainage and use of irrigation makes it ideally suitable for a wide range of agricultural practices such as arable crop production (beans, peas, potatoes, corn and small cereals), dairy, sheep, beef and fruit production (Luttmerding, 1981). The agricultural capability of western Fraser Valley ranks within the top 20% of agricultural land in British Columbia (Klohn Leonoff Ltd., 1992).

Despite climatic conditions that favour agriculture, current farming in western Fraser Valley is below its crop production potential due to a number of political and soil factors (Klohn Leonoff Ltd., 1992). The majority of the land (about 65%) is not owned by farmers but leased from the government and private landowners on short-term tenures. Lack of direct or long-term tenure on the land has forced farmers to manage the land on an annual basis with minimum conservation practices. Soil degradation, especially with respect to organic matter and structural stability, is a consequence of the lack of incentive for the farmers to invest in long-term management inputs such as subsurface drainage.

In the western Fraser Valley intensive crop production is practised and one of the major concerns associated with this type of farming is efficient utilization of nitrogen (N). Generally,

fertilizer N use in British Columbia in intensively farmed areas like the Lower Fraser Valley exceeds maximum recommended rates (Kowalenko, 1987a). Large N fertilizer application rates are also a consequence of decline in soil organic matter levels and compensate for reduced N mineralization from organic matter. This results in high amounts of residual soil mineral N after harvest of main season crops, thus increasing the amount of NO_3^- available for leaching.

Annual rainfall distribution in the Lower Fraser Valley is biased towards winter season with over 70% occurring in the off-season[1] (November to March). Annual maximum temperature and minimum rainfall are synchronized around July. Conversely, minimum temperature and maximum rainfall occur in January. Thus main growing seasons are relatively dry, minimizing the probability of NO_3^- leaching (Kowalenko, 1987b). Lack of optimum soil moisture conditions during the main season limits crop growth and N uptake. This may lead not only to residual fertilizer N in soil but also accumulation of mineralized N during the season and in the period succeeding the main growing season.

Loss of N from agricultural production systems has become a major concern since the cost of N fertilizers has gone up over the years. Loss of N can occur through NO_3^- leaching, denitrification, volatilization and erosion. The chances of loss of N from Lower Fraser Valley soils through NO_3^- leaching during winter are high (Kowalenko, 1987b and 1989). This is due to favourable climatic conditions and rapid rates of nitrification (Kowalenko, 1987b and 1989) in Lower Fraser Valley soils. The appearance of NO_3^- in groundwater as a result of agricultural practices has become a major concern with respect to groundwater pollution. The loss of NO_3^- through leaching beyond the effective root zone is also an economic loss to farmers and is not compatible with sustainable agriculture (Lal et al., 1991).

Extensive research has been done on the efficiency of winter rye to accumulate residual fertilizer N in a corn (*Zea mays* L.) production system (Staver and Brinsfield, 1990; Shipley et al., 1992; Ditsch et al., 1993). However, wide differences exist in climate, soil types and management systems. Most of the evaluation of biomass production and N uptake by barley (Holderbaum et al., 1990) in Maryland, oat (Jones, 1942; Mitchell and Teel, 1977) in Alabama and Delaware and, wheat (Neely et al., 1987; Tyler et al., 1987) in Georgia and Tennessee, respectively, have involved spring sampling and in many cases, no information on the dynamics of accumulated N is available when these cover crops were killed during winter. Most research on graminaceous cover crops and their effectiveness in capturing autumn residual N has concentrated on winter rye (Mitchell and Teel, 1977; Muller et al., 1989; Shipley et al., 1992; Ditsch et al., 1993; Staver and Brinsfield, 1990) and annual ryegrass (Nielsen and Jensen, 1985; Shipley et al., 1992). In most studies graminaceous cover crops were included as controls to measure the N-supplying capability of legume cover crops (Mitchell and Teel, 1977; Ebelhar et al., 1984; Hargrove, 1986; McVay et al., 1989; Holderbaum et al., 1990). Under these circumstances, graminaceous cover crop effects were restricted by cover crop management practices that were best suited for the legumes. Legume cover crops have a critical soil mineral N requirement for nodulation and N_2 fixation. High soil mineral N content depresses nodulation and reduces N_2 fixation (Richards, 1987). Soil mineral N content, which in part is related to fertilizer practice, becomes a limiting factor for grass cover crops. Furthermore, information on soil mineral N content in these studies is lacking. More information is needed about the capacity of graminaceous cover crops to accumulate main season residual mineral N with respect to planting dates, residual soil mineral N levels in the autumn and a wide range of cover crop possibilities including autumn-planted spring species. Because there is wide variability in management

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[1] Based on 1937-90 Normals at Vancouver International Airport.

systems and weather patterns in winter in different regions, recommendations based on these findings will be mostly region specific.

One of the goals of this study was to introduce spring species in winter cropping systems in western Lower Fraser Valley because of their rapid growth and N uptake in early autumn. However, due to their susceptibility to freezing damage in winter, it is important to know the composition of the various N fractions at winter-kill and their potential to retain accumulated N in residues following winter-kill.

Several reports indicate that proteins, peptides and amino acids can be stabilized through interaction with secondary products, mainly tannins and oxidation products of phenolics (Swain, 1965; Loomis 1974; Lyttleton, 1973; Gegenheimer, 1990; Verma, 1975). When spring species are killed by freezing, their cells lose compartmentalization through membrane damage. This results in mixing of cytoplasmic proteins with the contents of the vacuole. The pH of the vacuole contents may be sufficiently low to allow protein precipitation, and/or vacuole contents may contain phenolics which form complexes with the proteins on mixing (Forsyth, 1964). This may restrict the amount of N leached out of autumn-planted spring species residues during rainfall events following winter-kill and therefore influence retention of the N accumulated prior to winter. Thus determination of the amounts of water-insoluble, protein, nonprotein and mineral N fractions as influenced by various management practices may provide fundamental knowledge about retention of absorbed N during winter.

Most of the N in plants is in the form of proteins which can be classified into two components based on their physical properties. The two classes of plant proteins are (i) cold-water insoluble and (ii) cold-water soluble. The N associated with cold-water insoluble proteins can be retained in the residues of spring species following winter-kill. Soluble proteins, on the other hand, interact with plant secondary products (phenolics) following membrane damage

(Swain, 1965; Lyttleton, 1973; Loomis, 1974; Stevenson, 1982) to form insoluble complexes. Some N associated with soluble (cytoplasmic) proteins can also be retained in the residues of autumn-planted spring species following winter-kill.

Short daylengths and low light intensity conditions are prevalent in the autumn and both factors negatively influence the activity of nitrate reductase (Aslam and Huffaker, 1984; Heath et al., 1973; Pearson et al., 1981); the primary enzyme that is involved in the reduction of the NO_3^--N taken up by plants to NH_4^+ during assimilation process. Quantification of NO_3^--N in autumn-planted spring species crops at winter-kill is important because NO_3^--N is a readily mobile ion and can easily leach from winter-killed residues and ultimately out of the root zone during winter rainfall events. It is therefore felt that the potential for autumn-planted spring species to retain accumulated N during winter may be explained by plant composition of the three N fractions (insoluble protein-N, soluble protein-N and NO_3^--N) at winter-kill. There is tremendous documentation on the role of winter species in soil mineral N conservation (Ditsch et al., 1993; Staver and Brinsfield, 1990; Nielsen and Jensen, 1985; Brandi-Dohrn et al.; 1997; Martinez and Guiraud, 1990; Shipley et al., 1992), but currently there is no definitive research on autumn-planted spring species use to conserve autumn mineral N (especially NO_3^--N).

Until the establishment of the University of British Columbia Soil and Water Conservation Group and Delta Farmers' Soil Conservation Group in the spring of 1991 with joint funding from the governments of Canada and British Columbia (Temple, 1992), cover crop research in the western Lower Fraser Valley was lacking and most farms were left bare during the off-season. The goal of the program was to find feasible solutions to local soil degradation problems; especially soil compaction and declining soil organic matter levels (Bomke, 1996). One of the objectives was to develop suitable cover cropping techniques for maintaining soil organic matter

contents, providing overwinter soil protection, improving soil physical properties, and conserving autumn soil N. This thesis investigated the influence of cover crops on autumn soil mineral N conservation.

Apart from soil protection, improvement of soil physical properties (Hermawan, 1995) and reduction of soil erosion, when graminaceous cover crops are included in a crop rotation, management practices that will maximize the capture of main growing season residual mineral N and optimize N-use efficiency of succeeding main season crops should be considered. Identification of management strategies that influence the economic and environmental use of graminaceous cover crops on western Lower Fraser Valley soils during winter to conserve residual mineral N and protect NO_3^- from leaching is necessary.

1-2. OBJECTIVES AND HYPOTHESES

1-2.1. Statement of Objectives

The overall goal of this research was to contribute to the development and evaluation of appropriate winter cover cropping systems to conserve residual mineral N during winter for the western Lower Fraser Valley using species from the *Gramineae* family. This thesis tested the effects of various management practices (planting dates, fertilizer practice and crop species) on autumn residual soil mineral N conservation. The general objective was to evaluate the ability of winter tolerant (winter rye and annual ryegrass) and sensitive (barley, wheat and oat traditionally planted in spring) species planted in autumn as cover crops to accumulate and protect residual mineral N (NO_3^--N in particular) against loss through leaching in silty clay loam soils of western Lower Fraser Valley.

The specific objectives were:

1. to determine the effect of autumn planting date, soil mineral N content and crop species on N uptake by a cover crop before and after winter leaching period.

2. to determine the effect of autumn planting date, soil mineral N content and crop species on residual soil mineral N content before and after winter leaching period.

3. to determine the effect of autumn planting date and soil mineral N content on the retention of the N in the biomass of winter-sensitive crop species following winter-kill.

4. to determine the effect of autumn planting date and soil mineral N content on the partitioning of N into various plant N fractions by winter-sensitive crop species at winter-kill.

5. to determine the effect of autumn planting date, soil mineral N content and crop species on C/N ratio before and after winter leaching.

1-2.2. Hypotheses

1-2.2.1. Comparison of spring species and winter species

On the assumption that spring species (winter-sensitive species) can utilize early-autumn warm temperatures and long daylengths to grow rapidly and produce high biomass and that the vigorous growth is accompanied by larger N accumulation before winter leaching period compared with winter species (winter-tolerant species), I studied the effect of crop species on productivity and N uptake. The following specific hypotheses were tested:

(i) Spring species produce larger quantities of biomass before winter leaching period than winter species.

(ii) Spring species are more effective in capturing main-growing-season residual mineral N before winter leaching period than winter species.

1-2.2.2. Retention of accumulated nitrogen in spring species residues during winter

One of the major advantages of winter cover cropping in the Lower Fraser Valley is protection of NO_3^- from leaching during winter. Cover crops are able to meet this goal through assimilation of NO_3^- into organic N compounds. The role of autumn-planted spring species in soil mineral N (NO_3^- in particular) cycling during winter is therefore, in large part determined not only by the amount of N taken up before winterkill but by the quantities of various plant N fractions (mainly cold-water insoluble protein-N, soluble protein-N and NO_3^--N) at winter-kill and thus the amount retained in the cover crop residue after winter season.

On the assumption that plant protein content (total amount per ha^{-1}) and biochemical composition (hemicellulose, cellulose, lignin and phenolics) increase with plant age and that these constituents (mainly lignin and phenolics) interact with protein to form insoluble complexes following winter-kill, I studied the effect of autumn-planting date on N retention by spring species during winter.

The following specific hypotheses were tested:

(i) Spring species cover crops planted in August are more effective in capturing main-growing-season residual mineral N than those planted a month later.

(ii) August-planted spring species will retain both cold-water insoluble N (structural N) and water-soluble protein N (cytoplasmic protein N) but the cover crops planted one month later will retain only structural N.

(iii) Spring species cover crops that are planted in August have greater potential to retain accumulated N following winter-kill in winter than those planted one month later.

Various spring species N fractions were measured in order to determine the relationship between protein N (water-insoluble and soluble protein N) and N retention by these species during winter. Quantification of plant NO_3^--N was important because NO_3^- can readily leach out of the crop residues following membrane damage through freezing and thus can directly influence N retention by spring species during winter.

While cover crops can assimilate autumn mineral N and thus minimize NO_3^- leaching during winter, it is important to know how readily the organic N can be mineralized to plant available forms (NH_4^+ and NO_3^-) in spring. An inverse relationship exists between plant residue decomposition rates and the C/N ratio. Thus, residues with a high C/N ratio are often associated with a slow rate of decomposition. In contrast, residues having a low C/N ratio usually decompose at a more rapid rate. The C/N ratios of cover crops were studied because they are sometimes a useful parameter for predicting mineralization of residue N. However, despite the fact that C/N ratio can be useful in predicting decomposition rates, they should be interpreted cautiously since the C/N ratio indicates nothing about the availability of the C and N to microorganisms.

This study will broaden our understanding of the role of various cover crops of the *Gramineae* family in cycling of main-season residual mineral N so that management strategies can be developed to maintain or improve soil N availability while minimizing input costs and chances of polluting the environment.

Chapter 2: LITERATURE REVIEW

Cover crop systems can be based upon either legume or nonlegume species. Legumes contribute symbiotically fixed N_2 to soil in the form of NH_4^+ and NO_3^- through mineralization of plant residue N and the recycling of manure from animals to which legumes are fed (Peterson and Russelle, 1991). Nonlegume cover crops utilize soil N from the mineral N (NH_4^+ and NO_3^-) pool. The two cover cropping systems are similar in that they both eventually release N to succeeding summer crops through mineralization. In this thesis, the literature review will cover nonleguminous (*Gramineae* family) cover crops and their role in soil N conservation during winter.

2-1. Factors affecting mineral nitrogen accumulation in soil

When land is left fallow during summer, there is no crop uptake of N and mineral N (NH_4^+ + NO_3^-) accumulates in the soil. This mainly occurs as long as: there is decomposable organic matter in soil; the field is weed-free; there is not too much rain to either leach NO_3^- out of the root zone or cause loss to the atmosphere through denitrification; and the soil must be moist or subject to alternate wetting and drying. Soil mineral N can also accumulate when crops are growing (Staver and Brinsfield, 1990). Contents of soil mineral N decline in early stages of crop growth due to vigorous uptake and increase as the crop matures especially after flowering when uptake decreases.

Transport of N to the root surface is mainly by convective mass flow (for NO_3^- only) which is driven by transpiration. Thus, low amounts of rainfall in summer may limit crop yields and

reduce utilization of NH_4^+ and NO_3^-. Limited precipitation combined with evapotranspiration during the growing season also minimizes the probability of NO_3^- leaching (Kowalenko, 1987b and 1989). In field experiments with ^{15}N, Bartholomew (1971) found that recovery of the labelled fertilizer N by maize was closely related to the total amount of rainfall during the experimental period. Lower recoveries were observed under conditions where water stress was high. This finding is consistent with observations that in dry periods NO_3^- accumulates in the upper soil layers (Page and Talibudeen, 1977) and NO_3^- availability is reduced (Mengel and Casper, 1980).

Cropping sequence influences the amount of mineral N in the soil after the growing season. For example, Meek et al. (1994) showed that silage corn followed by winter wheat left less soil mineral N in the surface 45 cm in the autumn than bean following bean. Growing legumes during summer may increase the amount of residual mineral in autumn because legumes will utilize soil mineral N and will fix N_2 to an extent necessary to satisfy their requirement. Since summer temperatures favour mineralization of soil organic N, net accumulation of large amounts of mineral N at the end of the growing season is most likely under legume crops. Vaughan and Evanylo (1994), in their study using rye, hairy vetch and rye-hairy vetch in Virginia, to determine the combined effects of cover crops and fertilizer N on residual soil mineral N accumulation after corn, have indicated that combinations of legume cover crop and supplemental fertilizer N cause large amounts of mineral N to accumulate in the soil. Similar results were observed in experiments by Hargrove et al. (1984) who reported greater NO_3^- leaching potential when a legume cover was grown in a sorghum production system since a higher mineral N concentration was maintained in soil over a 2-year period compared to fertilizer-N-based systems with either rye or no cover crop. Nitrate contents at the end of the summer growing season in a sorghum production system were greater with legume cover crops compared to a nonlegume cover crop or

no cover crop (Hargrove, 1986). In both studies, NO_3^- leaching was not actually monitored therefore autumn soil NO_3^- is assumed to be the potential for leaching. These studies indicate that for the most part, soil N mineralization increases the amounts of post-harvest mineral N in soil which can be attributed to lack of synchronization of N uptake with conversion of organic N (unavailable to plants) to mineral N (available to plants). Mineralization of N from legume residues occurs late in the season after peak demand for N by summer crops.

2-2. Factors affecting nitrate leaching

Among the various combined forms of N only NO_3^- is leached out of soil in appreciable amounts by percolating water. Ammonium is held by cation exchange on clay and humus and can only be displaced by excess water and/or application of a salt solution. In contrast, NO_3^- is the most mobile ion and remains in solution because of its high solubility, since it is not retained by the negatively charged soil colloidal system (Legg and Meisinger, 1982; Russelle and Hargrove, 1989). The solution is displaced downwards by rainfall or irrigation water. Thus, if sufficient water is added to the soil, dissolved NO_3^- will be leached below the root zone. However, acid soils can have a local positive charge (pH-dependent) on the surface of particles and thus have an anion exchange capacity. In this case, NO_3^- adsorption by these soils can limit leaching losses. The preconditions for major losses through NO_3^- leaching is therefore largely determined by soil NO_3^- content, pH and the amount of water passing through the soil.

Loss of NO_3^- from the rooting zone is also determined by the soil type, since soil texture and structure affect the amount of water retained at field capacity (Wild, 1988). Proportions of sand, silt, clay and organic matter influence water and nutrient-holding capacity. Thus, the rate of NO_3^- leaching from a sandy soil is much greater than from fine textured soils (Widdowson et al., 1987) or soils with high organic matter content.

Rates of N leaching have been positively correlated with rates of N fertilization in various agricultural systems (Schuman et al., 1975; MacLean, 1977; Baker and Johnson, 1981; Barraclough et al., 1983). The potential for NO_3^- leaching also exists where excessive quantities of N-rich livestock or poultry wastes are applied in crop production systems (Ritter et al., 1986).

Nitrate displacement in soil is complicated. Many soils in the field have cracks and biopores through which rain or irrigation water flows quickly, carrying NO_3^- and other ions with it (Bouma and Anderson, 1977; Omoti and Wild, 1979; Smetten et al., 1983). Tillage breaks the continuity of these channels, resulting in slower infiltration rate and less downward movement of NO_3^- compared to untilled situations (McMahon and Thomas, 1976; Goss et al., 1978). For the same reason, intense rain in the autumn leaches some NO_3^- rapidly from the soil but bypasses the NO_3^- held in the soil matrix (Garwood and Tyson, 1977). The timing and intensity of rainfall events after fertilizer application influence NO_3^- leaching. Light rainfall following fertilizer application promotes movement of NO_3^- into soil micropores; macropores facilitate bypass of water-filled NO_3^--rich micropores, thus reducing NO_3^- leaching when subsequent rainfall events occur (Kanwar et al., 1985). On the other hand, abundant rainfall following fertilizer application may not allow equilibration of fertilizer N with resident soil solution in micropores and hence promote leaching through macropores. Thus improvement of soil structure may reduce or promote NO_3^- leaching after fertilizer application depending on timing and intensity of rainfall events.

2-3. Factors affecting denitrification loss

Denitrification is defined as the microbial reduction of NO_3^- or NO_2^- to gaseous nitrogen, either as N_2 or N_2O (Soil Sci. Soc. Am., 1979). Occurrence of denitrification requires presence of (1) denitrifying bacteria (2) NO_3^- [electron acceptor] (3) readily decomposable organic

compounds [energy source] and (4) anaerobic conditions [e.g saturated soils]. Losses of NO_3^- through denitrification during the growing season have been estimated to be small, based on measurements of ^{15}N loss in a field microplot experiment on a medium-textured Lower Fraser Valley soil (Kowalenko, 1989). The amount of mineral N in this study were monitored over the entire year in fallow plots starting in the spring of 1982. Myrold (1988) reported a similar observation during winter in western Oregon in a denitrification study under ryegrass (*Lolium multiflorum* Lam.) and winter wheat (*Triticum aestivum* L.).

Denitrification losses are greater in soils fertilized with manure than in non-manured soils (Burford et al., 1976; Rolston et al., 1984; Christensen, 1985; Paul and Zebarth, 1993) during the growing season due to the presence of readily decomposable organic carbon like volatile fatty acids (Paul and Beauchamp, 1989).

The effect of temperature on denitrification is great and NO_3^- loss can double with a temperature increase of 10 °C in the range of 10 to 35 °C. In the range of 0 to 5 °C, denitrification rates are small but still measurable (Harris, 1988). In the Fraser Valley (at Agassiz and Sumas), Paul and Zebarth (1993) estimated denitrification loss in the fall averaging 13 kg N ha^{-1} on sandy loam and silty loam soils. In Oregon, Myrold (1988) measured denitrification losses of about 1.7 and 0.7 kg N ha^{-1} yr^{-1} in winter wheat and annual ryegrass systems, respectively, on medium to fine-textured soils.

2-4. Effect of grasses on nitrate leaching

Grass cover crops affect NO_3^- leaching through their influence on downward flow of soil water. They reduce water runoff and increase the amount of water infiltration compared to a bare

soil (Langdale et al., 1979; McVay et al., 1989; Hermawan, 1995). This increases the amount of water moving through the soil profile and thereby increases the potential for NO_3^- leaching. Cover crops also influence downward movement of soil water when they are killed and left on the surface as a mulch. This results in increased water infiltration rate and decreased evaporation from the soil surface (Jones et al., 1969; Blevins et al., 1971; Phillips, 1984; Hargrove, 1985; Radcliffe et al., 1988). Conversely, cover crops transpire soil water and hence dry the soil, reducing the amount of water percolating through the soil profile and decreasing the potential for significant NO_3^- leaching (Wagger and Mengel, 1988). Increased infiltration is important during the winter when cover crop water use is small, but water use by cover crops is a major factor during spring when they are actively growing.

Cover crops influence NO_3^- leaching potential by utilizing residual mineral N in soils in the post-harvest period before the onset of winter. This reduces the amount of NO_3^- available for leaching before winter. Winter rye has been shown to reduce accumulation of residual soil mineral N ($NH_4^+ + NO_3^-$) in monoculture crop production systems and to minimize the risk of NO_3^- leaching in the Ridge and Valley region of Virginia (Ditsch et al., 1993).

Various grass cover crops have been demonstrated to effectively reduce NO_3^- leaching. Morgan et al. (1942), working with tobacco as a summer crop and winter rye (*Secale cereale* L.), oat (*Avena sativa* L.) and timothy (*Phleum pratense* L.) as winter cover crops, showed in a 10-year lysimeter study in Connecticut that the grass cover crops effectively reduced NO_3^--N leaching and soil NO_3^--N content. In their study rye was the most effective, reducing the amount of NO_3^--N leached by 66%. The oat crop was less effective than rye because it winter-killed. However, they did not take into account N contribution from the dead mulch of oat that may have mineralized and leached. Similar observations have been reported with winter rye (Karracker et

al., 1950; Staver and Brinsfield, 1990; Meisinger et al., 1990), annual ryegrass (Nielsen and Jensen, 1985) and perennial ryegrass (Martinez and Guiraud, 1990).

The net effect of cover crops on NO_3^- leaching will depend on prevailing weather conditions. In the Fraser Valley the most important cover crop effect on NO_3^- leaching is utilization of residual soil mineral N, since winter precipitation is extremely abundant and it is unlikely that there can be significant reduction of water percolating through the soil.

2-5. Grass cover crop nitrogen accumulation

One of the major criteria in selection of cover crops to reduce autumn soil NH_4^+ and NO_3^- is their effectiveness in taking up the mineral N. Cover crops minimize the problem of NO_3^- leaching by assimilation of mineral N (NH_4^+ + NO_3^-) to relatively unleachable organic forms. This protects NO_3^- from leaching during winter and hold it in the soil until the next spring to become available to a summer crop or stabilized in soil organic matter for future release. This is a simplified version of the concept underlying the role of cover crops in autumn residual-mineral-N cycling. This way, planting of winter cover crops can decrease NO_3^- leaching by reducing the amount available for leaching during the wet winter.

A cover crop with slow autumn but rapid spring growth will most likely not be effective in reducing NO_3^--N leaching from Lower Fraser Valley soils because in south coastal B.C., where winter precipitation is abundant and spread over several months, NO_3^- leaching can be a problem.

Patterns of N assimilation during plant growth vary among and within species. Although most rapid N accumulation generally occurs during rapid vegetative growth, some genotypes begin accumulating N earlier or continue to assimilate N later than others (Kurtz, 1982).

Most research on cover crops and their effectiveness to accumulate autumn residual N has concentrated on winter rye (Mitchell and Teel, 1977; Muller et al., 1989; Shipley et al., 1992; Ditsch et al., 1993; Staver and Brinsfield, 1990) and annual ryegrass (Nielsen and Jensen, 1985; Shipley et al., 1992). Extensive research on winter rye has shown its great potential to utilize residual mineral N present after corn harvest (Ditsch and Alley, 1991; Staver and Brinsfield, 1990; Wagger and Mengel, 1988). Some of the major characteristics of cover crops that would achieve that goal are rapid establishment and high biomass production; deep and high-density root system and ability of species to accumulate N in early stages of vegetative growth.

2-6. Effect of planting date on soil nitrogen

Early planting, as compared to late planting, of winter crops results in greater accumulation of N mineralized from soil organic matter during autumn. In Great Britain, Widdowson et al. (1987) compared amounts of N taken up over winter by several winter wheat crops planted early (September) or late (October) in autumn with NO_3^--N remaining in the soil. They reported greater N uptake and soil NO_3^--N content reduction (0-90 cm layer) when winter wheat was planted early compared to late. They also found an inverse relationship between N uptake in aboveground portions of wheat and residual NO_3^--N in soil for early-planted winter wheat but no consistent relationship for the late-planted crop on fine-textured soils. In fact, residual NO_3^--N in the 60-90 cm layer in late-planted plots increased due to a combination of limited uptake and leaching during winter.

In Denmark, Sorensen (1992) studied the effects of annual ryegrass planted in mid-July, beginning of August and mid-August on soil mineral N content before and after winter leaching for 4 years. He reported a significant decline in biomass production and N uptake with delayed planting. Soil mineral N content in the 0-100 cm layer before winter leaching (late November)

was significantly reduced when the cover crop was planted early as compared to late. Early planting exposes cover crops to long daylengths and high temperatures in late summer or early autumn, thus allowing rapid and deep root development, which can exploit a large volume of soil in the root zone.

2-7. Research on nitrogen in the Lower Fraser Valley

The climate of the Lower Fraser Valley is characterized by mild winter temperatures and high levels of precipitation. Under these conditions, NO_3^- is subject to leaching. Two studies by Kowalenko (1987b and 1989) in which soil mineral N was monitored on fallow plots over the entire year demonstrated that the (1) potential for NO_3^- leaching during the growing season is low (2) potential for NO_3^- leaching over winter is high (3) nitrification rate is rapid during the main season and (4) soil N mineralization over the summer is significant but denitrification is negligible. These studies clearly indicate that NO_3^- can accumulate in Lower Fraser Valley soils and unless proper management practices for summer crops are used, large losses will occur during winter.

2-8. Factors affecting nitrate assimilation in plants

Nitrate and NH_4^+ are the major sources of inorganic N taken up by roots of higher plants. Most of the NH_4^+ has to be incorporated into organic compounds in the roots, whereas NO_3^- is readily mobile in the xylem and can be stored in the vacuoles of roots, shoots and storage organs. In arable soils, NO_3^- is often the major source of available N to plants. In order to be incorporated into organic structures and to accomplish its essential functions as a plant nutrient, NO_3^- has to be reduced to NH_3. The reduction of NO_3^- to NH_3 is accomplished by two enzymes; nitrate reductase

which reduces NO_3^- to NO_2^- and nitrite reductase which reduces NO_2^- to NH_3 (Hewitt, 1975; Beevers, 1976). Therefore, factors which influence the activity of nitrate reductase affect incorporation of NO_3^- into organic N compounds and consequently cause accumulation of NO_3^- in plant tissues.

Nitrate assimilation by plants is influenced by environmental factors such as light intensity, (Aslam and Huffaker, 1984), water availability, rate of fertilizer N (Wright and Davison, 1964; Murphy and Smith, 1967) and type of N fertilizer. Nitrate accumulation in plants is greater from NO_3^- fertilizers than from $(NH)_2SO_4$ or urea (Holmes, 1968). Low light intensity and drought conditions increase the concentration of NO_3^- in the plant (Heath et al., 1973).

In green plants a correlation exists between light intensity and NO_3^- reduction. For example, a distinct diurnal pattern of reduction has been observed in shoots but not in roots (Pearson et al., 1981). The daytime proportion of nitrate reduction in shoots and roots differs from the proportion at night (Aslam and Huffaker, 1982). Aslam and Huffaker (1984) exposed excised barley leaves to a source of permanent light and found that nearly all of the NO_3^- absorbed was reduced but at low light intensity, only 25% of the NO_3^- absorbed was reduced. This indicates that NO_3^- reduction is much more sensitive to low light intensity than is NO_3^- uptake.

The location of NO_3^- reduction in plants can have an impact on how plants respond to light in terms of NO_3^- assimilation and net accumulation. The proportion of NO_3^- reduction carried out in roots and shoots depends on a number of factors, including the rate of NO_3^- supply, plant species and plant age. Generally, when soil solution NO_3^- concentration is low, a greater proportion of the NO_3^- is reduced in the roots. As soil solution NO_3^- concentration increases, the capacity of NO_3^- reduction in the roots becomes a limiting factor and an increasing proportion of

the total N is translocated to the shoots in the form of NO_3^- (Wallace and Pate, 1965). Although a high proportion of NO_3^- reduction in barley occurs in the roots (Bloom et al. 1992), NO_3^- reduction in the roots of oat is greater than that of barley (Pate, 1971).

There is a relationship between plant age and nitrate reductase activity. Nitrate reductase activity is generally lower in older plant leaves and this likely increases accumulation of NO_3^- in more mature plants (Van Egmond and Breteler, 1972; Santoro and Magalhaes, 1983; Kenis et al., 1992).

2-9. Nitrogen fractions and chemical composition of plants

Most of the N in plants is in organic forms. The N is incoporated into carbon-containing compounds which include nucleic acids, some vitamins, hormones, membrane components, coenzymes and pigments (chlorophyll). The largest proportion (about 90%) of the N in plants is in the form of proteins (Streeter and Barta, 1984).

Proteins, organic nonprotein N compounds, NH_4^+ and NO_3^- constitute all N fractions in plants. Plant protein N is composed of cold-water insoluble and soluble fractions. Cold-water insoluble N is mainly structural N which comprises of a small fraction of protein N associated with the cellulose of the cell wall and a large amount of insoluble protein N of the chloroplasts in which the protein is associated with lipid material of the membranes and with pigments such as chlorophyll.

Plant tissues have phenolic compounds, which constitute by far the largest and most widespread group of secondary plant products. Apart from genetic factors, light, mineral nutrition and other stress conditions (temperature and drought), the content of phenolic compounds in plants is dependent on age and growth stage (Wong, 1973). Lignin, cellulose and

hemicellulose increase as plants age (Albersheim, 1965; Parr and Papendick, 1978; Mengel and Kirkby, 1987; Walton, 1983). Lignin is a high-molecular-weight aromatic complex which is deposited on cellulose structures in the secondary cell walls of plants. Lignin varies from 2% of dry matter in young plants to 17% or more in fully mature plants (Walton, 1983). Lignin content in grasses may increase rather than decrease with high N supply (Kaltofen, 1988) as amino acids phenylalanine and tyrosine are precursors of lignin synthesis. Similarly, plant polyphenol (tannin) content increases with plant age (Swain, 1965).

After homogenization or winter-kill, plant N fractions especially those associated with proteins, can undergo two major transformations. Firstly, proteins can undergo enzymatic degradation to form amino acids. Secondly, proteins can interact with plant secondary products (phenolic compounds) to form insoluble complexes. Two major mechanisms are involved in the reaction of these phenolic compounds with proteins, forming insoluble complexes. Proteins combine with phenolics reversibly by hydrogen bonding and irreversibly following oxidation of the phenols by polyphenol oxidases to quinones (Lyttleton, 1973; Loomis, 1974; Stevenson, 1982). This kind of reactions can occur when plant cells lose their compartmentalization through membrane damage caused by freezing or homogenization, when cytoplasmic proteins mix with phenolic compounds in the vacuole (Forsyth, 1964). Thus the amount of N retained by autumn-planted spring species following winter-kill may be influenced not only by residue N (water-insoluble protein fraction), but also by the amount of N associated with soluble proteins.

Chapter 3: MATERIALS AND METHODS

3-1. Experimental layout and soil type description

Three experiments were conducted in the western Lower Fraser Valley of British Columbia starting from August and continuing to April of the next year in 1991-92, 1992-93 and 1993-94. The studies were conducted at different locations (L91, L92 and L93) each season (Figure 3-1). The soil at all three locations was Westham series. The landscape at the locations was nearly level (1% slope) and the soil was formed from fine-textured Fraser River floodplain deposits overlying coarse-textured deposits and, is generally classified as a Rego Humic Gleysol (Luttmerding, 1981). The L91 and L92 locations were poorly drained and previous summer crops were field peas (*Pisum sativa* L.) for L91 and beans (*Phaseolus vulgaris* L.) for L92. The L93 location was well drained due to installation of a subsurface drainage system and the preceding summer crop was potato (*Solanum tuberosum* L).

In the 1991-92 and 1992-93 winter cropping seasons, the experiments (I and II) had similar treatments, randomization and design. The factors tested were planting dates (August, September), with and without autumn-applied fertilizer N (0 and 100 kg N ha^{-1}) and crop species (fallow, spring barley and winter rye). The two planting dates, two simulated mineral N levels and three cover crop treatments were combined into twelve treatments in a factorial experiment that was arranged in a randomized complete block split split plot design with four blocks (Figure 3-2). Planting dates were the main plots (12 m x 36 m), soil mineral N treatments were subplots (12 m x 18 m) and cover crops were sub-subplots (12 m x 6 m).
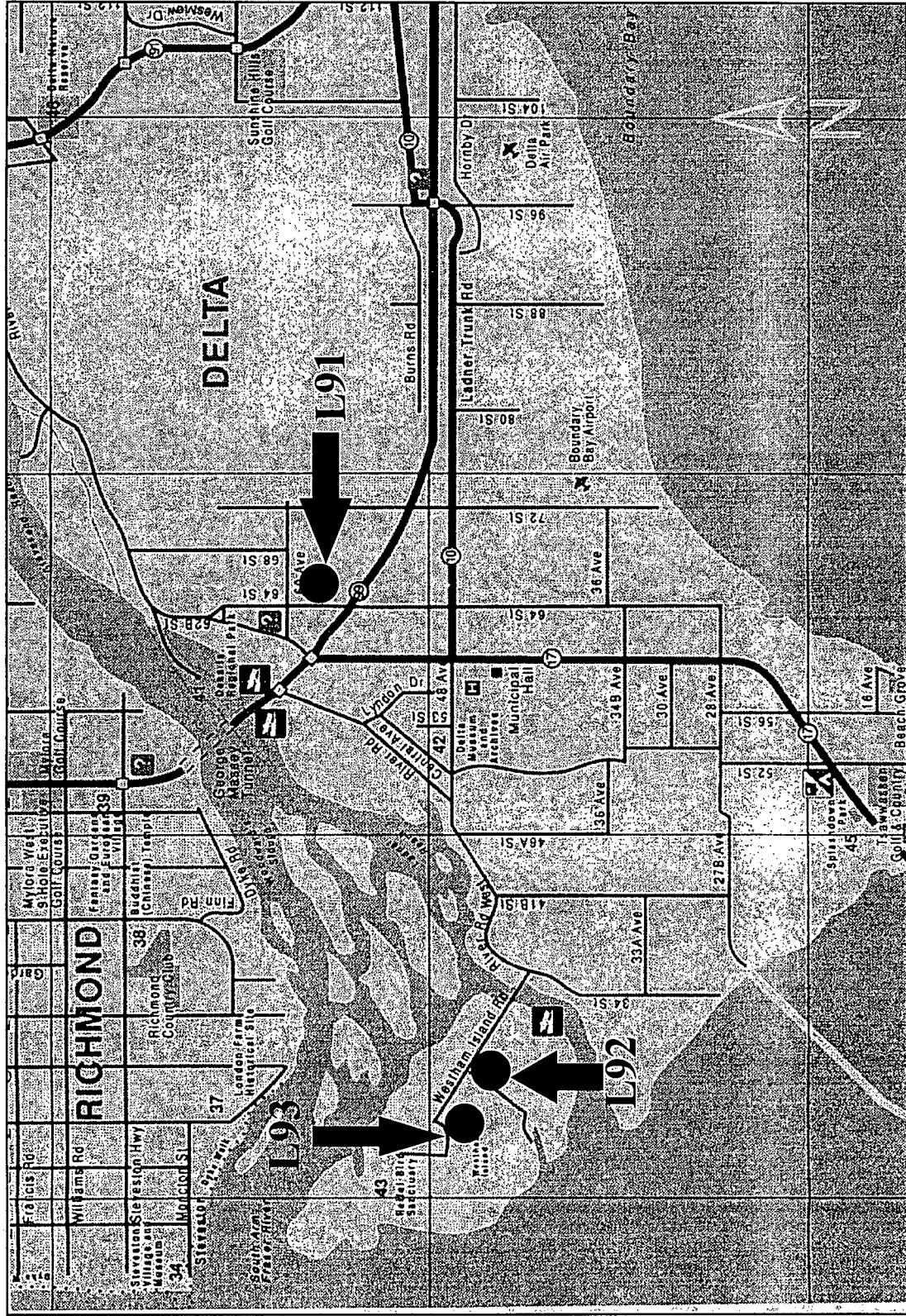
Figure 3-1. Map of Delta showing locations of experiments [●] for the three winter cropping seasons.
L91 = Nottingham Farm (1991-92); L92 = Kamlah Farm (1992-93); L93 = Swenson Farm (1993-94);

September Planting						August Planting						
N-100			N-0			N-0			N-100			B1
SB	F	WR	WR	SB	F	SB	WR	F	WR	F	SB	

August Planting						September Planting						
N-0			N-100			N-100			N-0			B2
SB	WR	F	WR	F	SB	F	SB	WR	F	WR	SB	

September Planting						August Planting						
N-0			N-100			N-0			N-100			B3
F	SB	WR	F	WR	SB	SB	F	WR	WR	SB	F	

August Planting						September Planting						
N-100			N-0			N-100			N-0			B4
SB	F	WR	WR	SB	F	SB	WR	F	WR	F	SB	

Figure 3-2. Layout of experiments established in August 1991 and August 1992 at Nottingham (L91) and Kamlah (L92) locations. (N-0, no N applied; N-100, 100 kg N ha^{-1} applied as NO$_3^-$; F = fallow; SB = spring barley; WR = winter rye;)

In 1993-94 winter cropping season (Expt III), planting date treatment was not tested as a factor because the data from experiments I and II had indicated only a minor effect of late-planting on main growing season residual mineral N. The same N treatment (0 and 100 kg N ha^{-1}) as in the previous two seasons was used and the cover crop treatments tested were increased to five, plus a winter fallow treatment. In addition to winter rye (*Secale cereale* L. cv. Danko) and spring barley (*Hordeum vulgare* L. cv. Virden), spring wheat (*Triticum aestivum* L. cv. Max), spring oat (*Avena sativa* L. cv. Jasper) and annual ryegrass (*Lolium multiflorum* Lam. cv. Westerwolds) were included. Spring wheat and spring oat were included because preliminary results from Expts I and II had indicated that spring barley that was planted in August and winter-killed in late November, increased soil mineral N (0-60 cm layer) in the spring. The two mineral N levels and six cover crop treatments were factorially combined into twelve treatments and arranged in a randomized complete block split plot design with four blocks (Figure 3-3). Mineral N levels were main plots (12 m x 36 m) and cover crop treatments were subplots (12 m x 6 m). In all the three experiments, the buffer strip between blocks was 9 m.

Cover crops were planted on August 19 and September 16, 1991, August 24 and September 22, 1992 and August 24, 1993, in 10-cm row spacings using a 3-m wide Vicon air seeder (LZ 301) mounted on a tractor. In 1991 and 1992 spring barley and winter rye were seeded at the rate of 100 kg ha^{-1}. The same seeding rate was used in the third year for spring barley, winter rye, spring wheat and spring oat. Annual ryegrass was seeded at 25 kg ha^{-1}. Nitrogen was surface broadcast immediately after planting as pelleted $Ca(NO_3)_2$ (15.5-0-0 farm grade). A summary of field operations during the three cover cropping seasons is presented in Table 3-1.

August Planting											
N-0						N-100					
SW	SB	ARG	WR	F	SO	WR	SW	F	SB	ARG	SO

B1

August Planting											
N-100						N-0					
SW	SB	SO	ARG	WR	F	WR	SW	SO	F	ARG	SB

B2

August Planting											
N-0						N-100					
ARG	SW	SB	F	SO	WR	ARG	F	WR	SO	SW	SB

B3

August Planting											
N-100						N-0					
SO	SW	WR	F	SB	ARG	SW	SB	ARG	SO	F	WR

B4
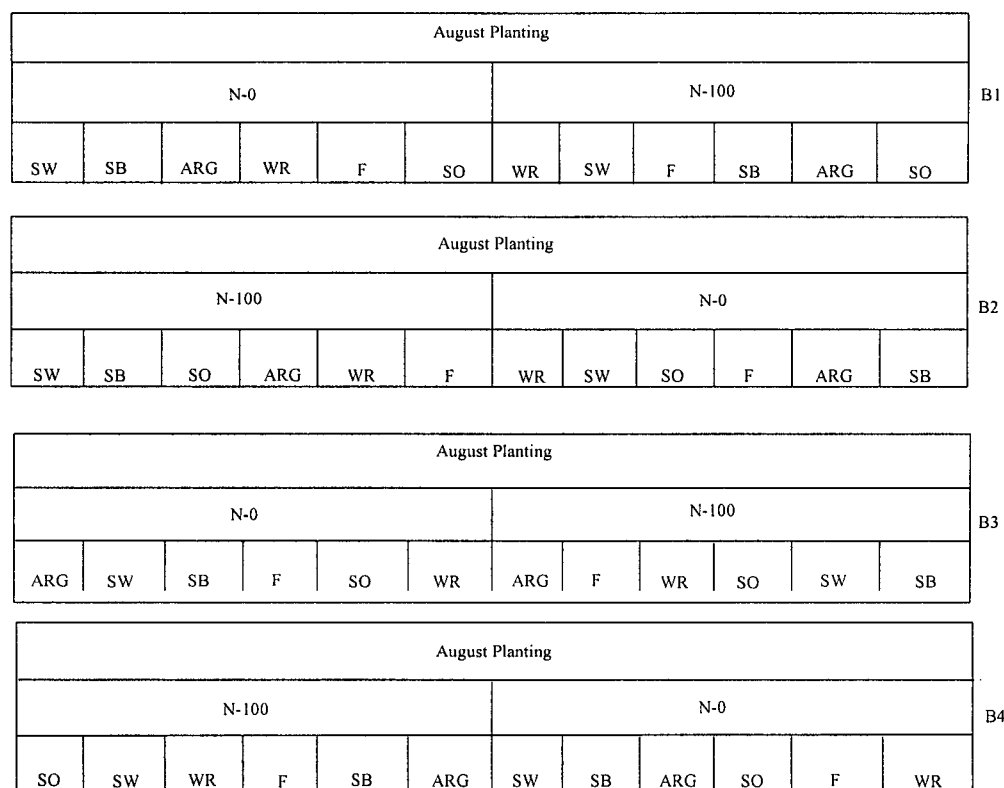
Figure 3-3. Layout of the experiment established in August 1993 at Swenson (L93) location (N-0, no N applied; N-100, 100 kg N ha^{-1} applied as NO_3^-; F = fallow; SB = spring barley; SW = spring wheat; SO = spring oat; WR = winter rye; ARG = annual ryegrass).

Table 3-1. Summary of field operations and precipitation measurements for 1991-92, 1992-93 and 1993-94 winter cropping seasons

Field Operation	Date	Days after planting	Cumulative precipitation (mm)¶
Soil sampling, First planting and N application	Aug/19/1991	0	0
Soil sampling, Second planting	Sep/16/1991	27	142
Soil and plant sampling	Nov/21/1991	94	334(398)
Soil and plant sampling	Apr/08/1992	232	862
Soil sampling, First planting and N application	Aug/24/1992	0	0
Soil sampling, Second planting	Sep/22/1992	28	30
Soil and plant sampling	Nov/24/1992	91	290(349)
Soil and plant sampling	Apr/30/1993	248	803
Soil sampling, Planting and N application	Aug/24/1993	0	0
Soil and plant sampling	Nov/23/1993	90	106(157)
Soil and plant sampling	Apr/14/1994	232	670

¶ Long-term (1937-90) cumulative precipitation between August and November is 388 mm; Values in brackets include total precipitation for the entire months of August and November; Cumulative precipitation was obtained by summation of daily measurements (Source: Vancouver International Airport);

3-2. The rationale for treatment choices

The study was set up to investigate the role of cover crops in autumn soil mineral N cycling under western Fraser Valley conditions. Winter-sensitive species (autumn-planted spring species) were included because of their rapid growth and high biomass production in early autumn. Winter-tolerant species were chosen because of their overwintering characteristic, to compare with winter-sensitive species which usually winter-kill at the start of winter (late November).

Nitrogen was applied in the form of $Ca(NO_3)_2$ to simulate the larger quantity of residual NO_3^--N in the soil that can result from fertilizer applications on a main season crop. Thus, the N treatment represented low (N-0) and high (N-100) amount of residual mineral N in the 0-60 cm soil layer, where no N and 100 kg N ha^{-1} was applied, respectively. This was done to enable me to test the capacity and efficiency of the selected cover crops in capturing autumn residual mineral N and to evaluate the dynamics of fertilizer N under cover cropping during winter on silty clay loam soils of the western Fraser Valley. Therefore, N was applied to test the potential of selected cover crops to capture mineral N remaining after summer crop harvest and thus protecting NO_3^- from leaching out of the root zone.

The timing of cover crop planting is largely determined by the time of summer crop maturity and harvest. Time of summer crop maturity and harvest is in most part dependent on crop species and environmental factors. The scope of the experiment was further increased by including two planting dates (August and September) to represent early- and late-harvested summer crops.

3-3. AUTUMN SOIL MINERAL NITROGEN DYNAMICS

3-3.1. Soil sampling and initial conditions

Soil sampling was done immediately before first and second plantings to determine initial amounts of main-growing-season residual mineral N (NH_4^+ + NO_3^-) in the 0-60 cm soil layer after summer crop harvest in 1991 and 1992 (August 19, 1991; September 16, 1991; August 24, 1992; September 22, 1992). Since there was only one planting date in 1993, soil was sampled once on August 24, 1993. Ten soil samples were taken randomly from each of the four blocks at 0-20, 20-40 and 40-60 cm depth intervals and composite samples of corresponding depths for each block were analyzed for various chemical and physical properties (Tables 3-2, 3-3 and 3-3).

Soil sampling was also done in late November and April of each winter cropping season to determine the fate of N in the soil over time. Late November sampling was assumed to represent the beginning of winter in the Lower Fraser Valley when spring species would usually winter-kill while April was selected to represent the time of land preparation for summer crops.

In all cases, soil was sampled with a 2.5-cm diameter Oakfield probe. In November and April, six cores were taken from each plot and samples from corresponding depth intervals were bulked in plastic bags and immediately placed in ice coolers. Soil samples were stored in a refrigerator at 1 °C overnight before they were thoroughly mixed and subsamples weighed for NO_3^- and exchangeable NH_4^+ extraction. Analysis of soil samples was done within 5 days after sampling in all cases.

Table 3-2. Some soil chemical properties at first planting for 1991-92 experimental location.

Parameter measured	Soil sampling depth intervals (cm)¶		
	0-20	20-40	40-60
pH	4.9	4.6	4.7
EC (ds m^{-1})	0.2	0.1	0.1
CEC (Cmol$_c$ kg^{-1})	17.0	15.7	21.6
Total C (g kg^{-1})	26.4	14.0	7.3
Total N (g kg^{-1})	1.6	1.2	0.6
Available elements (mg kg^{-1})			
P	120	30	10
K	370	190	80
Ca	1950	1580	1320
Mg	120	170	290
Na	10	10	20
SO$_4$-S	10	10	10

¶, Values are means of four blocks; pH, determined on 1:1 soil to water samples; EC, electrical conductivity determined on 1:1 soil to water filtrate x 2; CEC, total cation exchange capacity determined using 1M NH$_4$Ac and 1M KCl; C, LECO analyzer carbon; P, phosphorus (Bray 1); K, Ca, Mg and Na, base cations determined on NH$_4$Ac extracts; SO$_4$-S, 0.01M CaCl$_2$ extracts determined colorimetrically;

Table 3-3. Some soil physical and chemical properties at first planting for 1992-93 experimental location

Parameter measured	Soil sampling depth intervals (cm)¶		
	0-20	20-40	40-60
Sand (%)	1.7	1.7	3.3
Silt (%)	58.7	57.5	64.2
Clay (%)	39.6	40.9	32.6
Textural class	SiCL	SiC	SiCL
pH	5.4	5.2	4.5
EC (ds m^{-1})	0.6	0.5	0.5
CEC (Cmol$_c$ kg^{-1})	19.6	19.8	18.9
Total C (g kg^{-1})	17.1	15.1	12.8
Total N (g kg^{-1})	1.7	1.5	1.1
Available elements (mg kg^{-1})			
P	190	100	30
K	290	180	110
Ca	1530	1230	780
Mg	250	240	210
Na	260	260	280
SO$_4$-S	20	20	30

¶, Values are means of four blocks; Particle size determined by Hydrometer method; pH, determined on 1:1 soil to water samples; EC, electrical conductivity determined on 1:1 soil to water filtrate x 2; CEC, total cation exchange capacity determined using 1M NH$_4$Ac and 1M KCl; C, LECO analyzer carbon; P, phosphorus (Bray 1); K, Ca, Mg and Na, base cations determined on NH$_4$Ac extracts; SO$_4$-S, 0.01M CaCl$_2$ extracts determined colorimetrically;

Table 3-4. Some soil physical and chemical properties at planting for 1993-94 experimental location

| Parameter measured | Soil sampling depth intervals (cm)¶ | | |
	0-20	20-40	40-60
Sand (%)	3.6	1.7	3.8
Silt (%)	66.5	71.4	71.5
Clay (%)	29.6	26.9	24.7
Textural class	SiCL	SiL	SiL
pH	5.1	5.3	4.7
EC (ds m^{-1})	1.3	0.7	0.6
CEC (Cmol$_c$ kg^{-1})	18.8	18.4	18.6
Total C (g kg^{-1})	16.7	17.0	12.9
Total N (g kg^{-1})	1.5	1.4	1.0
	Available elements (mg kg^{-1})		
P	130	120	30
K	290	240	120
Ca	1590	1600	860
Mg	230	220	160
Na	30	20	30
SO$_4$-S	60	20	30

¶, Values are means of four blocks; Particle size determined by Hydrometer method; pH, determined on 1:1 soil to water samples; EC, electrical conductivity determined on 1:1 soil to water filtrate x 2; CEC, total cation exchange capacity determined using 1M NH$_4$Ac and 1M KCl; C, LECO analyzer carbon; P, phosphorus (Bray 1); K, Ca, Mg and Na, base cations determined on NH$_4$Ac extracts; SO$_4$-S, 0.01M CaCl$_2$ extracts determined colorimetrically;

3-3.2. Soil mineral nitrogen extraction and analysis

Ten-gram wet samples were weighed into 125-mL Nalgene plastic bottles and shaken with 100 mL of 2M KCl solution (Keeney and Nelson, 1982) on a reciprocating shaker for 1 h. Samples (including blanks) were then filtered through Whatman No. 42 filter paper into 60-mL Nalgene bottles and stored in a refrigerator at 1 $^{\circ}$C.

Samples were analyzed on automated flow injection ion analyzer (QuickChem AE) within 24 h after extraction. Nitrate was determined colorimetrically as NO_2^- by modified Griess-Ilosvay Cd reduction procedure by passage of the samples through a copperized cadmium column. The NO_2^- concentration was determined by diazotizing with sulfanilamide followed by coupling with N-1-naphthyl-ethylenediamine dihydrochloride to form a water soluble reddish purple azo dye which was read at 520 nm. Sample readings were calibrated against standard solutions of KNO_3 within appropriate concentration ranges.

Extractable NH_4^+ was also analyzed on the automated flow injection ion analyzer (QuickChem AE). Ammonium cation was converted to NH_3 by raising the pH to 13.5 with a concentrated buffer. Ammonia produced was heated with salicylate and hypochlorite to produce blue colour which was intensified by sodium nitroprusside. The blue colour is proportional to NH_3 concentration and was read at 660 nm. Sample readings were calibrated against standard solutions of NH_4Cl within appropriate concentration ranges.

Subsamples of the soil of about 20 g were used to determine the water content by oven-drying at 105 $^{\circ}$C for 48 h. This water content was used to correct soil NH_4^+-N and NO_3^--N concentration measurements to an oven-dry weight basis.

Core samples (10 cm diam.) were taken from 0-20, 20-40 and 40-60 cm soil layers at each planting in November and April for bulk density determination. Bulk density values were used to

convert NH_4^+-N and NO_3^--N concentrations (mg kg^{-1}) to kg ha^{-1} values. Apparent fertilizer N recovery in the soil (ANR$_{SOIL}$) was calculated according to equaton 3-1:

$$ANR_{SOIL} (\%) = \frac{[(Mineral\ N)_{N-100}] - [(Mineral\ N)_{N-0}]}{applied\ N\ rate} \times 100 \qquad (3\text{-}1)$$

where, N-0 = no N applied and N-100 = 100 kg N ha^{-1} applied as NO_3^-.

Residual NO_3^- + NH_4^+ or NO_3^--N under fallow was compared with that under cover crop by calculating percent reduction in soil NO_3^- + NH_4^+ or NO_3^--N that was attributed to the cover crop. A similar procedure was used by Meisinger et al. (1991). The impact of cover crops on soil NO_3^- + NH_4^+ or NO_3^--N was calculated as percent reduction in N (PR) according to equation 3-2:

$$PR (\%) = \frac{[(Soil\ N)_{FALLOW}] - [(Soil\ N)_{CROP}]}{(Soil\ N)_{FALLOW}} \times 100 \qquad (3\text{-}2)$$

where, soil N (NO_3^- + NH_4^+ or NO_3^--N) was estimated from the 0-60 cm soil layer.

3-3.3. Plant sampling and biomass measurement

Estimates of biomass production of cover crops and N uptake were based on aboveground plant material. In November and April of each season, plant samples of living cover crops

(winter rye and annual ryegrass) were harvested at ground level from centre rows using clippers from a 0.5 m x 0.5 m quadrate. In November of each season, two sets of winter-sensitive species (spring barley, spring wheat or spring oat) were harvested from the 0.25 m² area. One set of samples was weighed fresh, placed in meshbags and left in the field until spring. The other set was used for moisture, biomass and total N determinations. Moisture content was used to calculate the dry-weight of meshbag samples left in the field. In the spring of 1992, biomass and residue N for spring barley were measured on meshbag samples that were anchored on the soil surface. In the spring of 1993, measurements of biomass and residue N for spring barley were obtained from meshbag samples placed on wire mesh tables. Measurements of biomass and residue N for winter-sensitive species (spring barley, spring wheat and spring oat) were obtained from samples collected from a 0.5 m x 0.5 m quadrat in the spring of 1994.

A summary of sampling dates and growth stages, according to Zadoks decimal code (Zadoks et al., 1974), for cover crops during the three study seasons is presented in Table 3-5. Plant samples were oven-dried at 70 °C, weighed and ground in a Wiley mill (1.0-mm sieve) in preparation for dry weight biomass measurement, and total N and carbon (C) analysis.

Table 3-5. Summary of sampling dates and growth stages of cover crops for the three winter cropping seasons (1991-94).

Sampling Date	Cover Crop Species	Planting Date	Morphological Stage	Zadoks Growth Stage
Nov/21/1991	Spring Barley	August/19	Ear emergence	51
	Spring Barley	September/16	Stem elongation	33
	Winter Rye	August/19	Tillering	28-29
	Winter Rye	September/16	Tillering	23-25
Apr/08/1992	Spring Barley	August/19	WK	WK
	Spring Barley	September/16	WK	WK
	Winter Rye	August/19	Booting	45
	Winter Rye	September/16	Booting	45
Nov/24/1992	Spring Barley	August/24	Booting	41
	Spring Barley	September/22	Tillering	23-24
	Winter Rye	August/24	Tillering	29
	Winter Rye	September/22	Tillering	25-26
Apr/30/1993	Spring Barley	August/24	WK	WK
	Spring Barley	September/22	Ear emergence	51
	Winter Rye	August/24	Flowering	61
	Winter Rye	September/22	Flowering	61
Nov/23/1993	Spring Barley	August/24	Booting	45
	Spring Wheat		Booting	45
	Spring Oat		Stem elongation	45
	Winter Rye		Tillering	29
	Annual Ryegrass		Stem elongation	-
Apr/14/1994	Spring Barley	August/24	WK	WK
	Spring Wheat		WK	WK
	Spring Oat		WK	WK
	Winter Rye		Ear emergence	51
	Annual Ryegrass		Stem elongation	-

WK, Winter-killed

3-3.4. Cover crop total nitrogen and carbon analysis

Duplicate 1-g samples were weighed into 100-mL digestion tubes and 5 mL of digestion mix (Parkinson and Allen, 1975) were added. Samples were digested for 2.5 h at 360 °C. Nitrogen (as NH_4^+-N) concentrations were determined as described in section 3-3.2 on automated flow injection ion analyzer (QuickChem AE). Using dry weight biomass (kg ha^{-1}) and N concentrations (mg kg^{-1}) the data were extrapolated to a kg ha^{-1} (kg per unit surface area) basis. Plant samples (50 mg) were analyzed by LECO™ CR-12C analyzer (LECO Corp., St. Joseph MI) for total carbon content.

The effectiveness of the cover crops to accumulate main-growing-season residual soil N was assessed by determining productivity (dry weight biomass) and N accumulation (dry weight biomass x N concentration) of the autumn-planted cover crops. Apparent fertilizer N recovered (ANR_{CROP}) in cover crop was calculated from equation 3-3:

$$ANR_{CROP} (\%) = \frac{[(N\ uptake)_{N\text{-}100}] - [(N\ uptake)_{N\text{-}0}]}{applied\ N\ rate} \times 100 \qquad (3\text{-}3)$$

where, N-0 = no N applied and N-100 = 100 kg N ha^{-1} applied as NO_3^--N.

3-3.5. Statistical analysis

The data was analyzed using the general linear model procedure (SAS/STAT Software, 1989). The mathematical model of the procedure applied to the split-split plot design used in the experiment is represented by the equation:

$$Y_{ijkl} = \mu + B_i + P_j + BP_{ij} + N_k + PN_{jk} + BPN_{ijk} + C_l + PC_{jl} + NC_{kl} + PNC_{jkl} + BPNC_{ijkl}$$

where,

Y_{ijkl} = observation associated with the $ijkl$th experimental unit (eu);

μ = overall mean (common effect in all observations);

B_i = effect due to the ith block (Block effect, i = 1, 2, 3, 4);

P_j = effect due to the jth level of planting date (Planting date effect, j = 1, 2);

Bp_{ij} = random error associated with ijth main plot (main plot error (a));

N_k = effect due to the kth level of nitrogen treatment; (Nitrogen effect, k = 1, 2);

PN_{jk} = interaction associated with the jkth planting date-nitrogen combination (planting date x nitrogen interaction effect);

BPN_{ijk} = random error associated with the ijkth subplot (subplot error (b));

C_l = effect due to the lth level of cover crop treatment (l = 1, 2, 3);

PC_{jl} = interaction associated with the jlth planting date-cover crop combination (Planting date x cover crop interaction effect);

NC_{kl} = interaction associated with the klth nitrogen-cover crop combination (nitrogen x cover crop interaction effect);

PNC_{jkl} = interaction associated with the *jkl*th planting date-nitrogen-cover crop combination (planting date x nitrogen x cover crop interaction effect);

BPNC_{ijkl} = random error associated with *ijkl*th subsub-plot (subsubplot error (c)).

Bartlett's test was carried out to test homogeneity of variances. Test of independence of the means and the standard deviations were also used to determine the relationship between the means and standard deviations. Most of November soil mineral N data failed Bartlett's test of homogeneity of variances and all soil mineral N data (November and April) had means that were highly correlated with the standard deviations ($0.80 < r < 0.95$). Logarithm transformation was applied to soil mineral N contents to minimize correlation between the mean and the standard deviation. In this thesis, means of original data are presented but interpretation is based on ANOVA from data transformed logarithmically (Antal. Kozak, Faculty of Forestry, University of British Columbia, personal communication).

Since soil data were collected from the same experimental units in November and April of each season, a repeated-measures analysis of variance was used to evaluate the changes in cover crop productivity, N uptake and soil mineral N (0-60 cm layer) over the winter as randomization of sampling dates was not possible (Littell, 1989; George. W. Eaton, Department of Plant Science, University of British Columbia, personal communication). A similar approach has been used by Schomberg et al. (1994) to evaluate the influence of water on decomposition and N dynamics for surface and buried residues.

General linear model options in SAS (SAS/STAT, 1989) were set to test planting date, autumn soil mineral N content and cover crop species main effects using main plot MSE [error (a)], subplot MSE [error (b)] and subsubplot MSE, [error (c)], respectively, according to split split plot design for 1991-92 and 1992-93 data. Similarly, GLM options were set to test soil

mineral N content and cover crop main effects using main plot MSE, [error(a)] and subplot MSE [error (b)], respectively, according to split plot design, for 1993-94 data.

Repeated-measures analysis of variance was done using the general linear models procedure in SAS (SAS/STAT, 1989). Univariate tests of hypotheses for time (T) and interactions with planting date (D), autumn soil mineral N content (N) and crop species (C) (i.e Within Subjects Effects) were based on repeated measures ANOVA, but tests of hypotheses for planting date (D), autumn soil mineral N content (N) and crop species (C) (i.e Between Subjects Effects) were based on ANOVA for data at each sampling date.

3-4. NITROGEN DYNAMICS OF SPRING GRAMINACEOUS COVER CROPS

3-4.1. Nitrogen retention study

The following sections (sec. 3-4.1 and 3-4.2) describe the procedures for determining the potential of autumn-planted spring species to conserve mineral N (NO_3^--N in particular) during winter. Spring barley (*Hordeum vulgare* L. cv. Virden), spring wheat (*Triticum aestivum* L. cv. Max) and spring oat (*Avena sativa* L. cv. Jasper) were harvested in the experiments described in the materials and methods (see. sec. 3-1). In 1991-92 and 1992-93 seasons, the study involved only spring barley and, therefore, the experimental design was reduced to split plot with planting date as the main plot and autumn soil mineral N content as the subplot. But in the 1993-94 winter cropping season, planting date was omitted as a treatment and the study included spring barley, spring wheat and spring oat as subplots and autumn soil mineral N content as the main plot. The N treatments (N-0, N-100) were administered to create a secondary level of residual mineral N in autumn to test the capacity of N uptake by cover crops.

Two sets of aboveground plant material were harvested from two randomly selected areas (0.5 m x 0.5 m quadrat each) in each of the spring species plots on November 21, 1991, November 24, 1992 and November 24, 1993 for the three winter cropping seasons. Fresh weights of both sets of samples were determined immediately in the field. One set of samples was placed in fiberglass meshbags of 0.5 m x 0.5 m dimension having mesh size of 1.5 mm x 1.5 mm. These bags of plant material were left in the field to measure changes in biomass and total N of the winter-killed mulch over the winter. The other set of samples was brought into the laboratory and oven-dried at 70 °C for 96 h. The oven-dry weight was used both for biomass and moisture content determinations. The moisture content was then used to calculate the dry weight of original biomass in the meshbags left in the field. The oven-dried samples were ground in a Wiley mill to pass through a 1-mm sieve and duplicate digestions using the method described by Parkinson and Allen (1975) were run to determine N concentration as described in section 3-3.2. This allowed me to calculate total N of meshbag materials at the beginning of the experiment (November).

In November 1991, the meshbags were anchored on the soil surface in harvested areas within the plots. However, because the original objective was to estimate the amount of N lost from the plant materials through leaching after damage caused by freezing, it was decided in 1992-93 and 1993-94 seasons to place the meshbags on a wire mesh table with an area of 3 m x 2 m raised on wooden legs 0.5 m above the ground. The purpose of the wire mesh table was to avoid contact of the residues with the soil and thus an environment conducive to decomposition. The wire mesh size was 12 mm x 12 mm. The mesh table was laid out in the buffer strips between blocks above winter rye which was at late tillering stage in November so that contamination from soil particles during rainfall events was avoided.

In spring of each cropping season, the meshbag samples were removed from the field at the time the winter cover crops were harvested. The removal dates of meshbag samples from the field were April 8, 1992, April 30, 1993 and April 14, 1994 for the three seasons. In the spring of 1994, undisturbed spring-species-cover-crop residues in field plots were collected using 0.5 m x 0.5 m quadrates. The materials were oven-dried at 70 °C for 96 h, and biomass and total N were determined as described above. The difference in residue N between late November (time of winter-kill) and April (spring) was assumed to have been that which was leached from the materials in meshbags on mesh tables. Biomass and N retention by cover crop residues were calculated according to equations 3-4 and 3-5 as follows:

$$\text{Biomass remaining (\%)} = \frac{\text{Biomass remaining in April (kg ha}^{-1}\text{)}}{\text{Biomass measured in November (kg ha}^{-1}\text{)}} \times 100 \qquad (3\text{-}4)$$

$$\text{Nitrogen retention (\%)} = \frac{\text{Residue N in April (kg ha}^{-1}\text{)}}{\text{Cover crop N in November (kg ha}^{-1}\text{)}} \times 100 \qquad (3\text{-}5)$$

3-4.2. NITROGEN FRACTIONATION STUDY

3-4.2.1. Sample preparation and extraction techniques.

Separate plant materials were randomly harvested from each of the spring-species plots in experiments II (1992-93) and III (1993-94). Materials were immediately frozen in liquid N_2 to minimize protease activity. Samples were transported to the laboratory in ice coolers and stored at -50 °C until they were freeze-dried (Edwards Freeze Dryer, MODULYO) for 72 h and chopped into small pieces with scissors. Freeze-dried samples were then frozen with liquid N_2, ground while still frozen in a chilled commercial waring blender and stored at -50 °C until the time of extraction and analysis.

The major aim was to extract plant tissue as completely as possible to evaluate the relative contribution of the various fractions to the total N of the cover crops at winter-kill. A cold extraction with 0.05M phosphate buffer at pH of 7.4 was used to determine the various N fractions. The fractions were cold-water insoluble N (WIN) remaining in residue, TCA-precipitable protein N (PN), organic nonprotein N (NPN), NO_3^--N (NN) and NH_4^+-N (AN). Cold- and hot-water extraction procedures were compared for total protein (WIN + PN) and organic nonprotein N (NPN). Hot-water extraction (Goering and Van Soest, 1970) and 2M KCl extraction (Keeney and Nelson, 1982) were compared with cold-water extraction for NO_3^--N and NH_4^+-N.

3-4.2.2. Preparation of homogenizing medium

Two stock solutions of 0.05M monosodium phosphate ($NaH_2PO_4.2H_2O$ - solution A) and 0.05M disodium phosphate (Na_2HPO_4 - solution B) were prepared using deionized water. To make 1 L of 0.05M phosphate buffer solution, 190 mL of solution A was mixed with 810 mL of

solution B (Bollag and Edelstein, 1991). Homogenizing medium was then made with the 0.05M

phosphate buffer solution by adding protease inhibitors and antioxidants. To a 1 L volumetric

flask, protease inhibitors, 1.0mM phenylmethylsulfonyl fluoride - PMSF (Fahrney and Gold,

1963; Turini et al., 1969), 1.0mM p-chloromercuribenzoate (Wallace and Cotta, 1988) and

10mM ethylenediaminetetraacetic acid (EDTA) were added (Bollag and Edelstein, 1991).

Further, 0.4% sodium isoascorbate (w/v) and 4mM sodium metabisulfite (Anderson and Rowan,

1967) were added as antioxidants and the mixture was made to volume with phosphate buffer

solution. These antioxidants were included to prevent oxidation of low molecular weight

phenolic compounds to quinones, which in turn could combine with proteins, thus modifying

their biochemical and physical properties. Higher molecular weight phenolics, frequently called

tannins, can form insoluble complexes with proteins (Swain, 1965; Loomis and Battaile, 1966;

Loomis, 1974; Gegenheimer, 1990). This removes the proteins from solution. To overcome this

problem, insoluble polyvinylpyrrolidone (PVP) was used (Loomis, 1974).

3-4.2.3. Phosphate buffer (cold-water) extraction

The nitrogen fractionation scheme is presented in Figure 3-4. Three-gram samples were

weighed into a waring blender and 4.5 g of insoluble polyvinylpyrrolidone (PVP) was added.

The mixture was homogenized for 1 min. in 70 mL of cold 0.05M phosphate buffer

homogenizing medium, cooling intermittently for 1 min in an ice bath after every 15 seconds. A

blank, consisting of 4.5 g PVP, was similarly processed. The homogenized slurry was transferred

into 250-mL centrifuge bottles using 100 mL of homogenizing medium and centrifuged

immediately at 14,000 x g for 45 min at 3 °C. The homogenate was decanted carefully from plant

residue into 500-mL volumetric flasks. Plant residue remaining in the centrifuge tubes was rinsed

twice by suspension in 80-mL aliquots of homogenizing medium each time and centrifuged as stated above. Blanks, to correct for reagents used, were similarly processed.

During the period of rinsing and centrifuging of the residue, homogenates were kept in the refrigerator at 1 °C. Immediately after completion of extraction, 80 mL of the homogenate were measured into 100-mL centrifuge tubes and proteins were precipitated using 15% (w/v) trichloroacetic acid - TCA (Bhatty, 1972). The mixture was centrifuged at 10,000 x g for 45 min at 3 °C. The supernatant was decanted into 125-mL Nalgene plastic bottles and stored at -18 °C until analysis for total N, NH_4^+ and NO_3^- (see Figure 3-4). The methods of analyses are given in the following section. The pellet of protein precipitate was discarded.
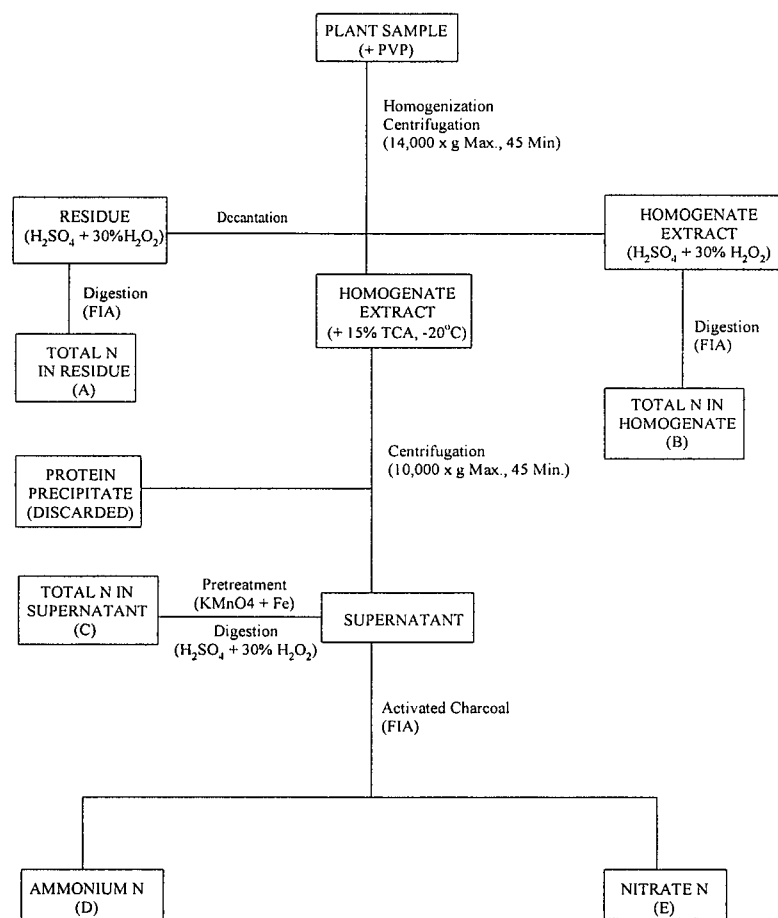
Figure 3-4. Nitrogen fractionation scheme to determine total N in residue (A), total N in homogenate (B), total N in supernatant (C), NH_4^+-N (D) and NO_3^--N (E).

3-4.2.4. Sample nitrogen determination

Residue samples and the PVP-only blank were dried on previously tared drying pans at 100 °C for 8 h and weighed. These dried residues were then transferred into 100-mL Kjeldahl flasks and digested for total N according to the method described by Parkinson and Allen (1975). Total digestion time was 3 h. Total N was determined as NH_4^+-N colorimetrically with an automated flow injection ion analyzer (Lachat Instruments, QuickChem AE) as described in section 3-3.2.

Homogenate and supernatant extracts (5 mL) were pretreated for 1 h with $KMnO_4$ and reduced Fe to include NO_2^--N and NO_3^--N (Bremner and Mulvaney, 1982; McGill and Figueiredo, 1993) before digestion and total N was determined as described above. Cold-water soluble protein N was estimated from the difference between total N for homogenate extract and supernatant.

Supernatant (100 mL) was treated with 0.5 g of activated carbon (Darco-60G). Blanks of similar volume of homogenizing medium were also treated with 0.5 g of activated carbon. Charcoal-treated samples and reagent blanks were filtered through Whatman No. 42 paper. Ammonium N and NO_3^--N were determined colorimetrically on automated flow injection ion analyzer (Lachat Instruments, QuickChem AE). Organic nonprotein N was estimated from the difference between supernatant total N and mineral N (NH_4^+-N + NO_3^--N).

To check recoveries of total N, NO_2^--N and NO_3^--N from plant material, 100-mg plant samples and 1 mg N kg^{-1} of standard KNO_2 and KNO_3 were similarly digested to include NO_2^- and NO_3^- as described for homogenate extract and supernatant.

Nitrogen of the various fractions was first calculated on freeze-dry-weight basis (g kg^{-1}). Values of the sum of all fractions were compared with total N of 100-mg plant material. Total N recovery from plant material was 96 and 95% of all fractions for November 1992 and 1993

samples, respectively. Total N recovery from KNO_2 and KNO_3 was 99%. Individual fractions were therefore, expressed as percentages of the sum of all fractions (%TN). The means (n = 4) of field N uptake (kg ha^{-1}) for November sampling were used to calculate N for all fractions on a kg ha^{-1} basis.

3-4.2.5. Hot water extraction

Extraction of hot-water protein-N (True protein-N), organic nonprotein-N, NH_4^+- and NO_3^--N fractions was based on the method described by Goering and Van Soest (1970) with modification to the original apparatus. Two-gram samples were weighed into 500-mL round bottom flasks and 200 mL of distilled water added. Refluxing condensers were attached vertically at the top and the contents were boiled for 1 h at 100 °C in heating mantles connected to variable autotransformers (Type 3PN 1010, Staco Inc., Dayton, Ohio) in order to regulate the temperature. The contents were then filtered with vacuum through 12.5 cm Whatman No. 54 filter papers set in 60° funnels. Residue on the filter paper was washed four times with 50 mL aliquots of hot water.

Residue samples were dried on previously tared drying pans at 100 °C for 8 h and weighed. These dried residues (including filter paper) were then transferred into 100-mL Kjeldahl flasks and digested for total N according to the method described by Parkinson and Allen (1975). Blank digestions of filter paper alone were similarly processed. Total digestion time was 3 h.

Two sets of filtrate samples were placed in 125 mL Nalgene bottles. One set was treated with 0.5 g of activated carbon (Darco G-60) to remove colour in order to determine NH_4^+-N and NO_3^--N. Blanks with 0.5 g of activated carbon in a similar volume of hot water were included. The samples and blanks were filtered through Whatman No. 42 paper. The filtrates were stored

in the freezer at -18 °C until NH_4^+-N and NO_3^--N analysis. The other set was used for total N measurement. Total N was determined as described in section 3-4.2.4 for homogenate and supernatant N to include NO_3^-. Hot-water extractable organic nonprotein N (NPN) was estimated from the difference between filtrate total N and mineral N ($NH_4^+ + NO_3^-$).

In addition to cold- (see Sec.3-4.2.3) and hot-water (see sec. 3-4.2.5) extracts for NH_4^+ and NO_3^-, plant samples were extracted with 2M KCl (Keeney and Nelson, 1982) by shaking 0.25 g of tissue samples in 100 mL of 2M KCl solution for 1 h. The mixtures were filtered through Whatman No. 42 filter paper. Nitrogen for all the fractions was determined colorimetrically with an automated flow injection ion analyzer (Lachat Instruments, QuickChem AE) as described in section 3-3.2.

3-4.3. Statistical analysis

Since plant materials were harvested in a split split plot design (Expts I and II) and the sub-subplot had only one spring species treatment (spring barley), the data for N retention and N fractionation studies were analyzed according to a split plot design for 1991-92 and 1992-93 seasons with planting date as the main plot and autumn soil mineral N content (N-0 and N-100) as the subplots. In the 1993-94 season (Expt III) the data were also analyzed as a split plot design, but with autumn soil mineral N content as main plots and spring cover crop species (barley, wheat and oat) as subplots. In the fractionation study, cold- (CW - method A) and hot-water (HW - method B) extracts were compared for protein-, organic nonprotein- NH_4^+- and NO_3^--N measurements as paired observations using a two-tailed T - test ($P < 0.05$). Similarly, cold-water insoluble N (WIN) and total protein N (WIN + PN) fractions were compared with proportions of N retained in meshbag residues that were placed on tables, as paired observations using a two-tailed T - test ($P < 0.05$).

Chapter 4: EXPERIMENTAL CONDITIONS

4-1. Weather during study period

The Lower Fraser Valley has a temperate climate, generally characterized by warm, rainy winters and relatively cool, dry summers (Hare and Thomas, 1979) and, has the highest annual temperature (about 10 °C[2]) in Canada (Schaefer, 1978). Western Fraser Valley also has the longest period of frost-free days in Canada (Luttmerding, 1981). Mean monthly temperatures and total monthly precipitation for long-term 1937-90 normals are shown in Figure 4-1. Total daily precipitation for 1991-92, 1992-93 and 1993-94 winter cropping seasons are shown in Figures 4-2 and 4-3. August 1991 was very wet compared to long-term records and, August 1992 and 1993. In that month, total rainfall was 170 mm with 134 mm occurring between August 26 to 31. Generally, most of the rainfall events occurred during the winter months (November to March). Mean monthly air temperatures for the three winter cropping seasons are shown in Figure 4-4. The lowest temperatures occurred between November and February. In the 1991-92 and 1993-94 seasons the lowest temperatures were generally above normal while those for 1992-93 season were below normal, with the lowest temperature recorded in January (-0.4 °C).

4-2. Daily soil and air temperatures

Daily soil temperatures were monitored during the 1991-92 and 1992-93 winter cropping seasons at 3 and 40 cm below the surface using thermocouple (copper-constantan) sensors. Thermocouples (one in each plot) were installed in fallow, August-planted spring barley and winter rye plots and readings were recorded with a Campbell Scientific ·21X Datalogger (Campbell Scientific Inc., Logan, Utah). Daily air temperatures were similarly measured using

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[2] Based on 1937-90 normals at Vancouver International Airport (Source: Environment Canada, Climate Services Vancouver, and Canadian Climate Normals for B.C)
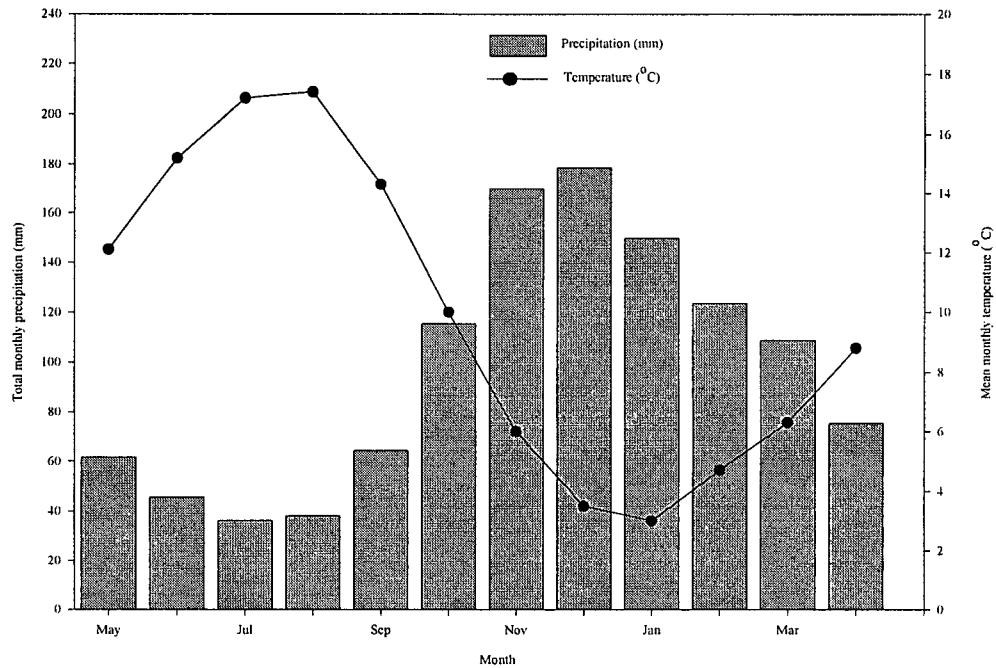
Figure 4-1. Mean monthly air temperatures and total monthly precipitation for 1937-90 normal as recorded at Vancouver International Airport (Source: Environment Canada, Climate Services Vancouver, and Climate Normals for British Columbia).
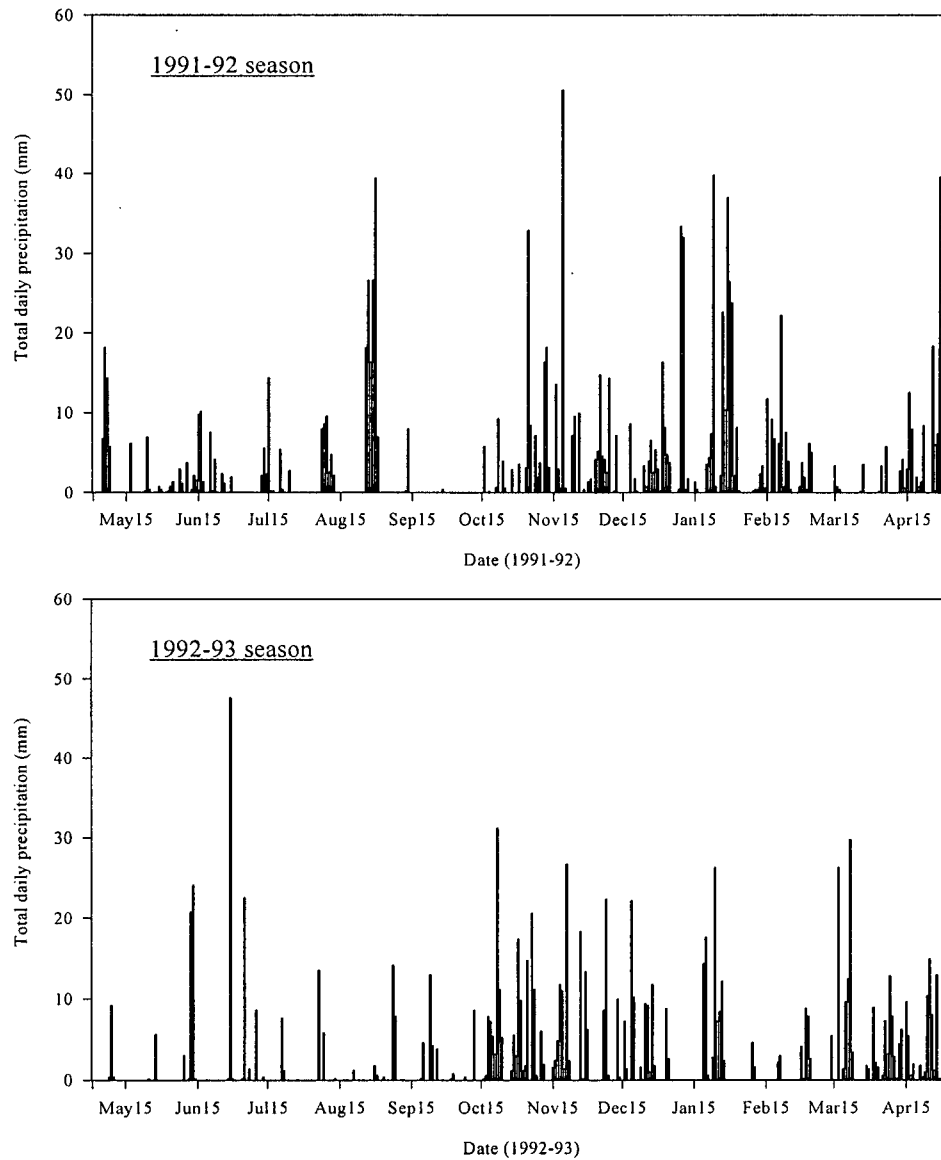
Figure 4-2. Total daily precipitation for 1991-92 (above) and 1992-93 (below) winter cropping seasons as recorded at Vancouver International Airport (Source: Environment Canada, Climate Services Vancouver, and Climate Normals for British Columbia).
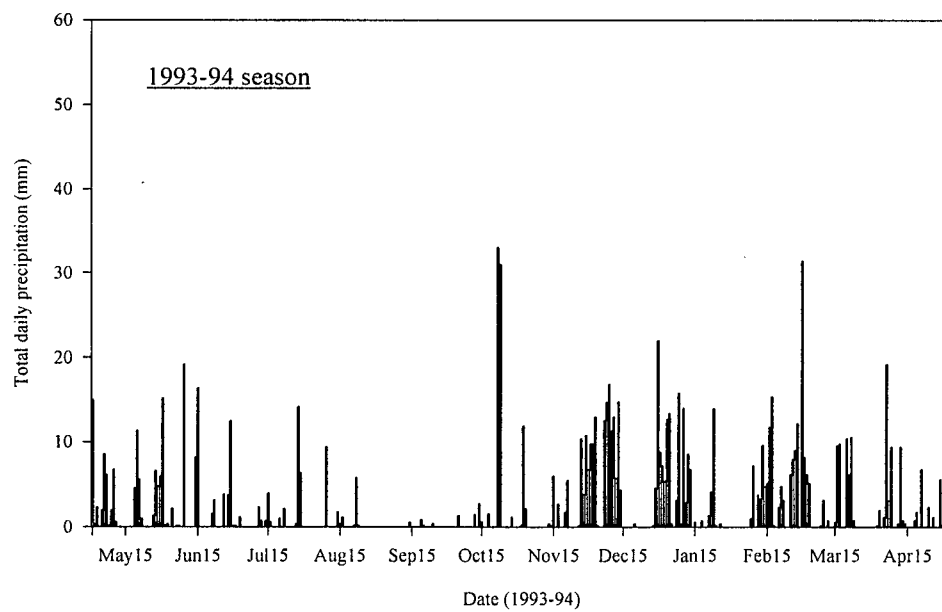
Figure 4-3. Total daily precipitation during 1993-94 winter cropping season as recorded at Vancouver International Airport (Source: Environment Canada, Climate Services Vancouver, and Climate Normals for British Columbia).
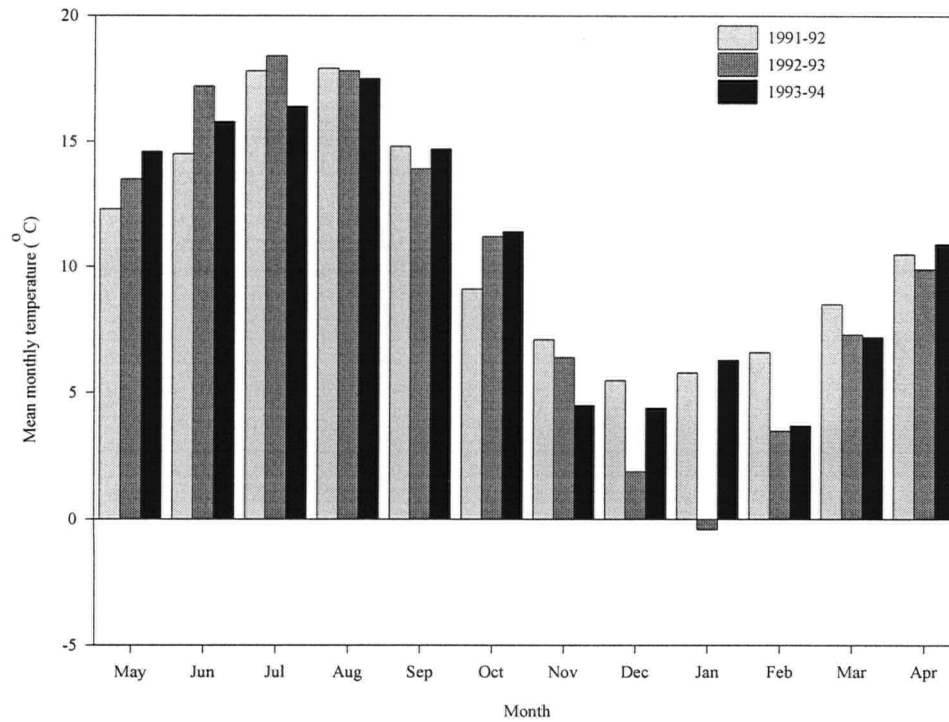
Figure 4-4. Mean monthly air temperatures during 1991-92, 1992-93 and 1993-94 winter cropping seasons as recorded at Vancouver International Airport (Source: Environment Canada, Climate Services Vancouver, and Climate Normals for British Columbia).

copper-constantan sensors shielded from radiation by a Stevenson Screen. Mean daily air and soil temperatures for the 1991-92 season are shown in Figures 4-5 and 4-6. Average daily soil temperatures (at 3 cm depth) approached 0 $^\circ$C in December 1991 and January 1992, and generally increased above 8 $^\circ$C from the beginning of March.

Mean daily air and soil temperatures at the 3 and 40 cm depth for the 1992-93 season are presented in Figures 4-7 and 4-8. Mean daily soil temperatures (at the 3 cm depth) remained near
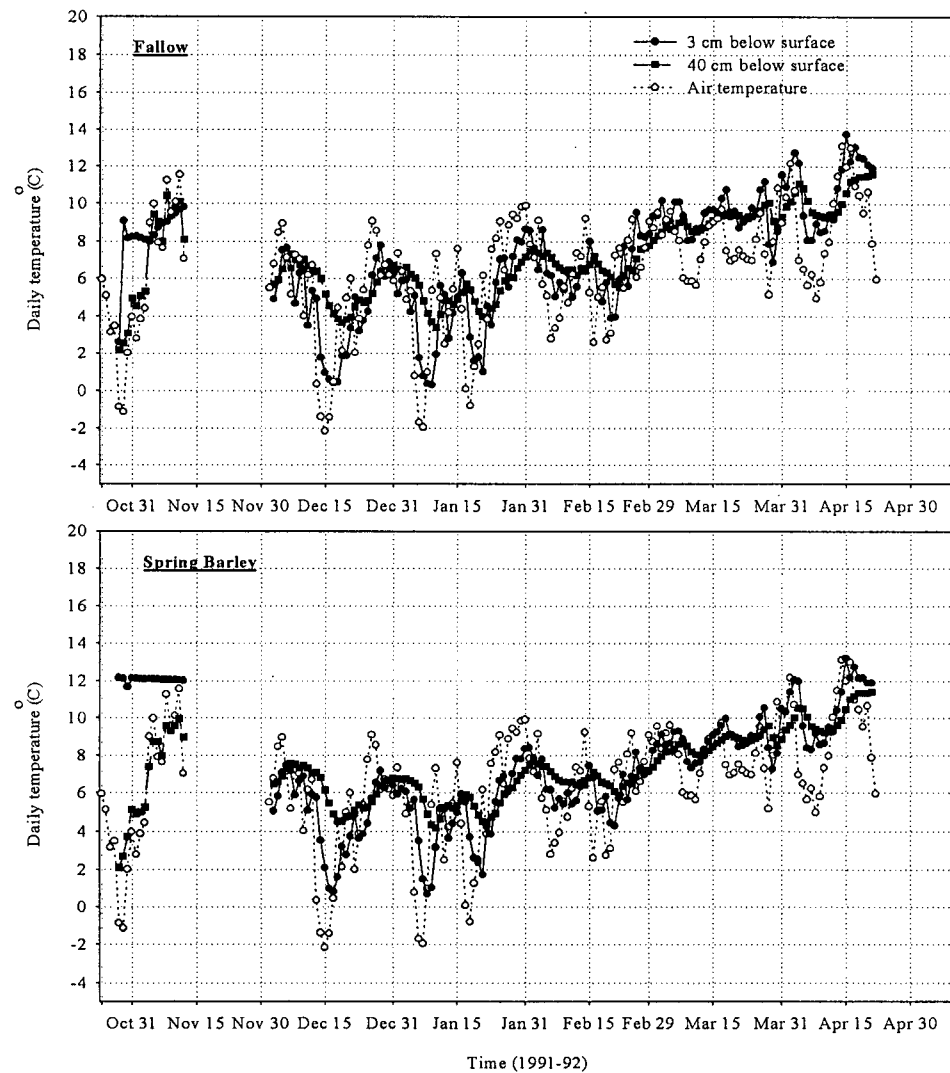
Figure 4-5. Daily air and soil temperature means during the 1991-92 winter cropping season under fallow (above) and autumn-planted spring barley (below).
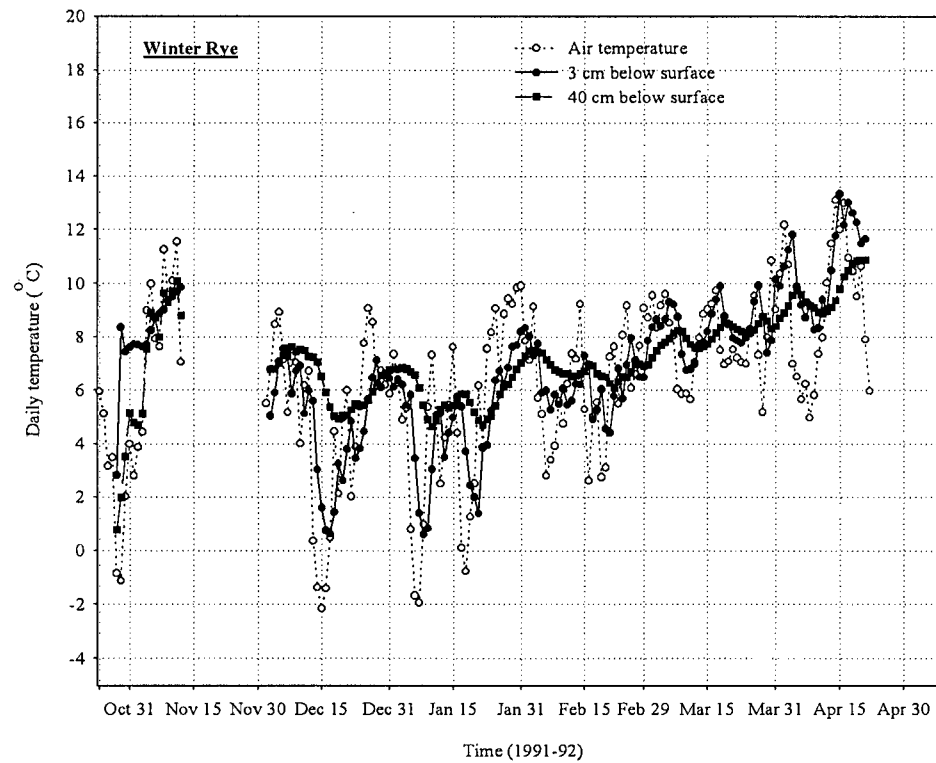
Figure 4-6. Daily air and soil temperature means during the 1991-92 winter cropping season under autumn-planted winter rye.
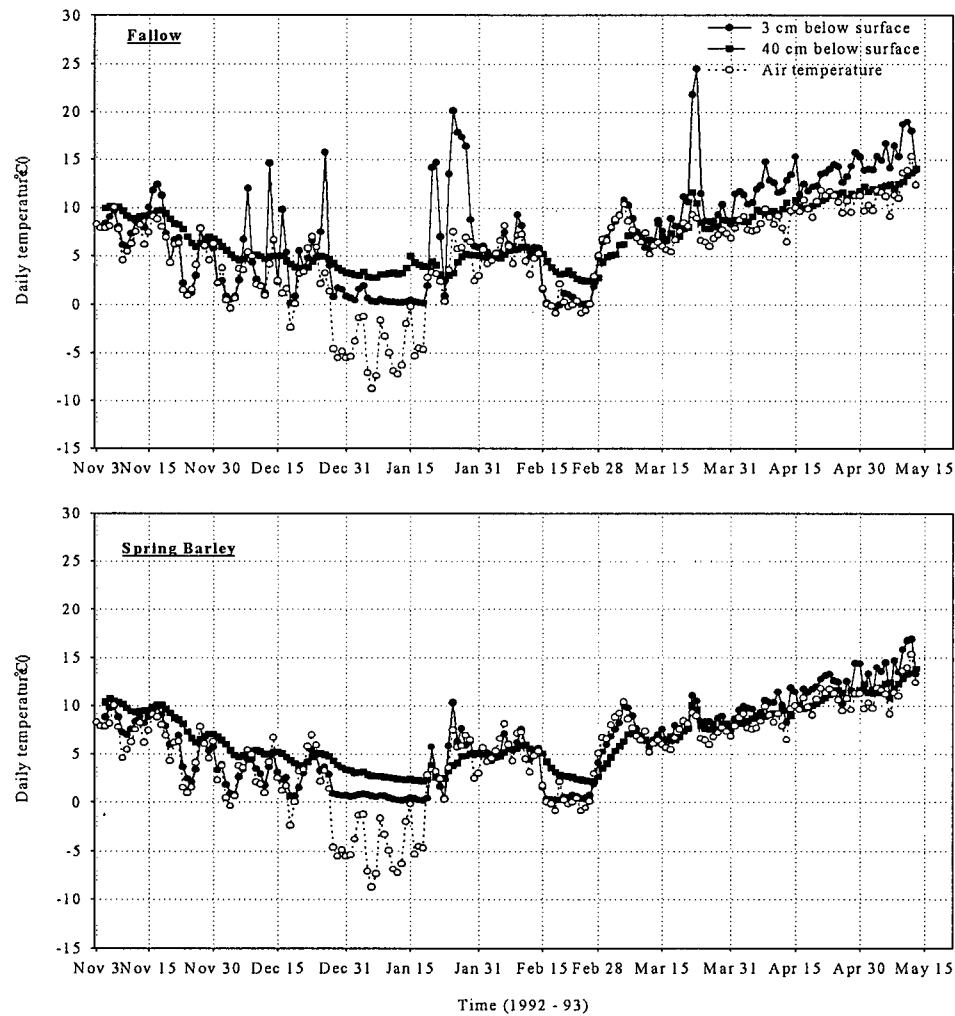
Figure 4-7. Mean daily air and soil temperatures for the 1992-93 winter cropping season under fallow (above) and autumn-planted spring barley (below).
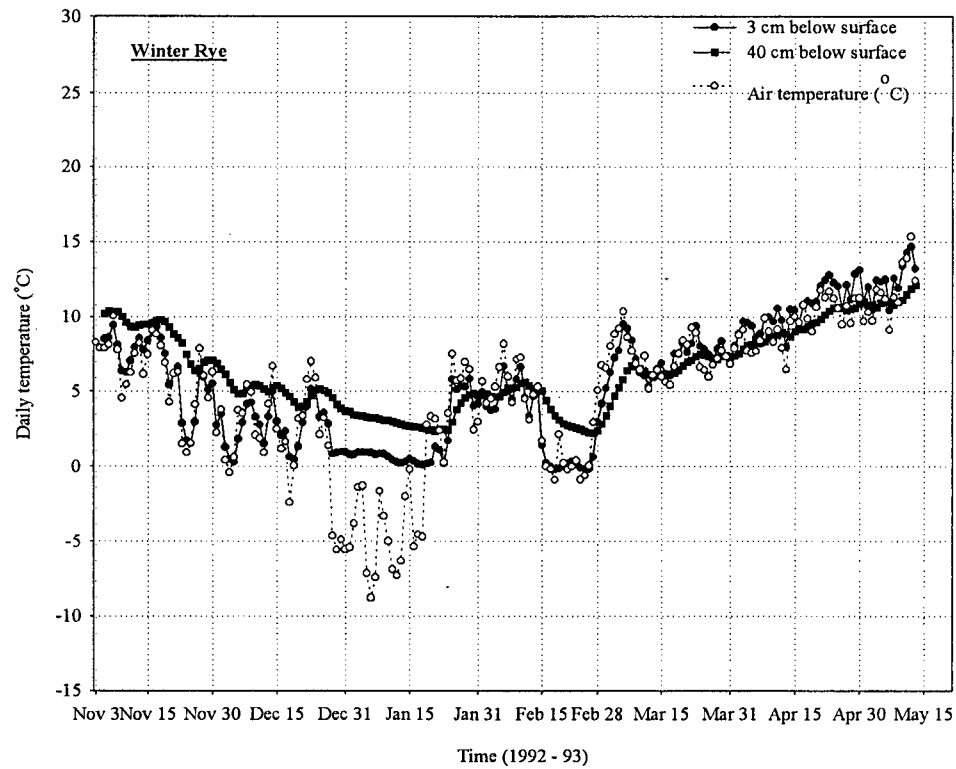
Figure 4-8. Mean daily air and soil temperature variations during the 1992-93 winter cropping season under autumn-planted winter rye.

0 $^{\circ}$C in the first and last half of January and February, respectively, and thereafter increased above 5 °C in March. In both winter cropping seasons, soil temperatures measured at the 3 cm depth generally reflected changes in air temperature, except under fallow in 1992-93 season. It appears the temperature sensor in the fallow plot was exposed to direct radiation.

4-3. Monthly minimum and maximum temperatures

Monthly minimum and maximum soil temperatures at the 3 cm depth for the 1991-92 season are shown in Figure 4-9. In October and November 1991, both monthly minimum and maximum soil temperatures at the 3 cm depth were higher under spring barley than under fallow or winter rye. Tremendous growth of spring barley and early snow fall (October 28, 1991) which resulted in lodging of the cover crop provided sufficient insulation that limited heat exchange between surface soil and air during cooling and warming. Thereafter, minimum and maximum temperatures under fallow and cover crops were not considerably different, although fallow plots appeared to cool and warm faster than those under cover crops. Monthly minimum and maximum soil temperatures at the 40 cm depth were not greatly influenced by cover cropping (Figure 4-10). In the 1992-93 winter cropping season, comparison of soil temperature at the 3 cm depth between fallow and cover cropped plots was not valid as it was apparent that the temperature sensor was exposed to direct radiation (Figure 4-11). Monthly minimum temperatures were not influenced by crop species but maximum temperatures under spring barley were generally higher than those under winter rye. Similar to the 1991-92 season, monthly minimum and maximum temperatures (at the 40 cm depth) were not greatly influenced by cover cropping, although maximum temperatures under winter rye were generally cooler than either under fallow or autumn-planted spring barley residues (Figure 4-12).
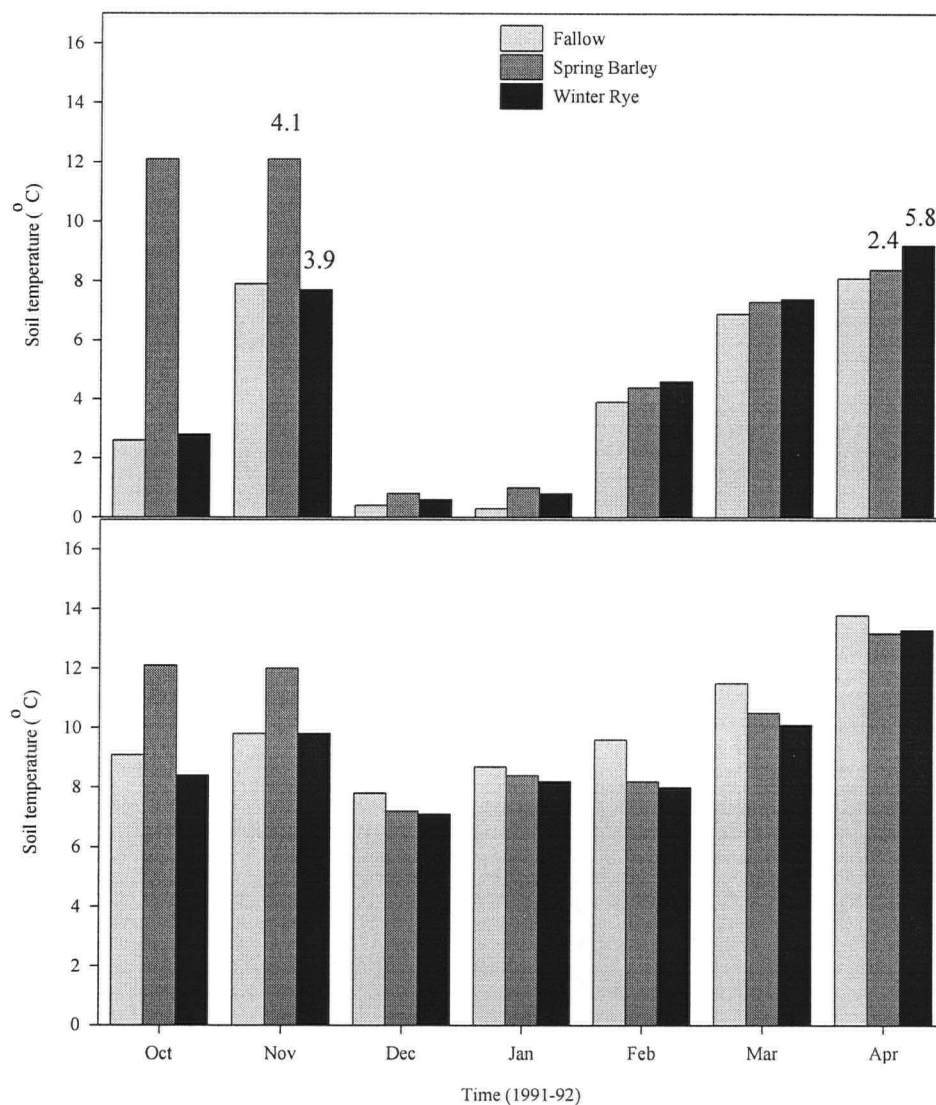
Figure 4-9. Monthly minimum (above) and maximum (below) temperatures at 3 cm depth during the 1991-92 winter cropping season. (values above the bars for spring barley and winter rye represent averages over the N treatment of the amount of cover in t ha⁻¹).
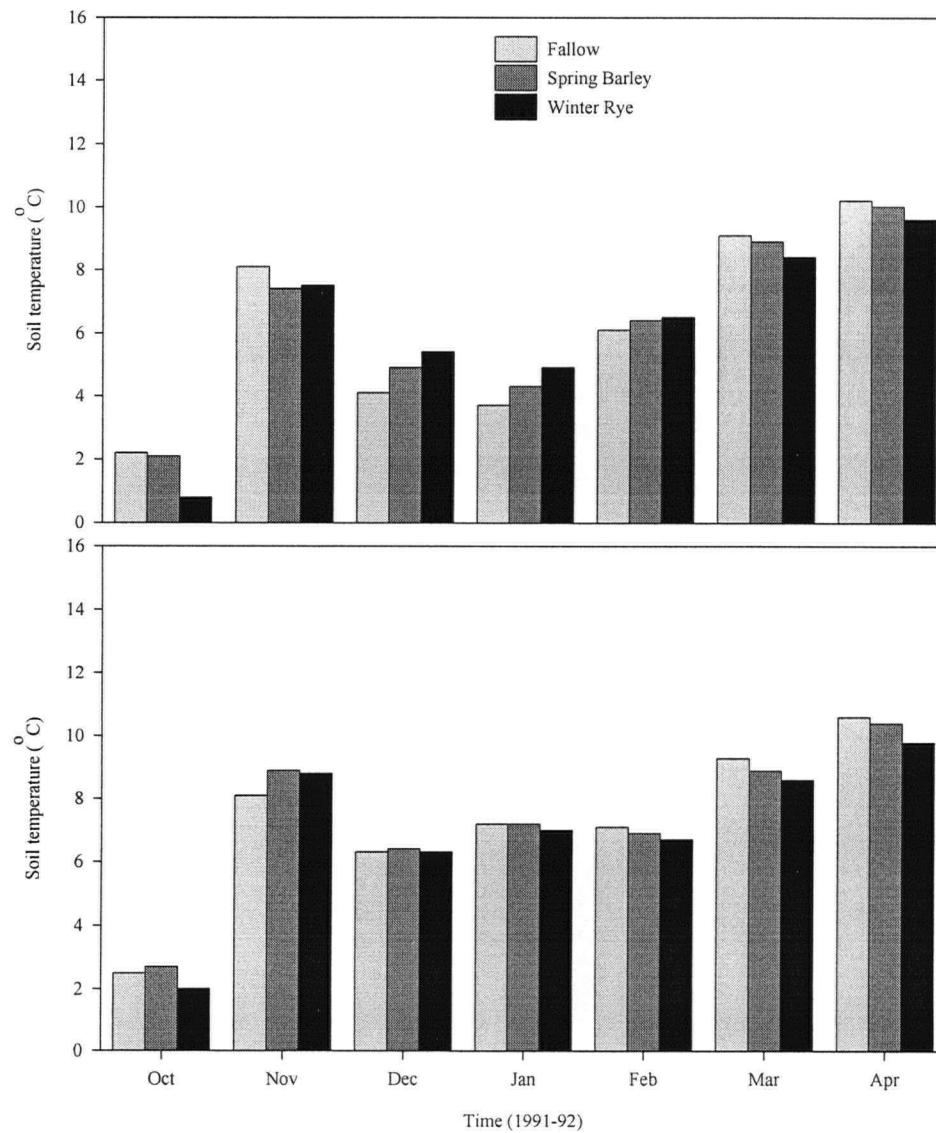
Figure 4-10. Monthly minimum (above) and maximum (below) temperatures at 40 cm depth during the 1991-92 winter cropping season.
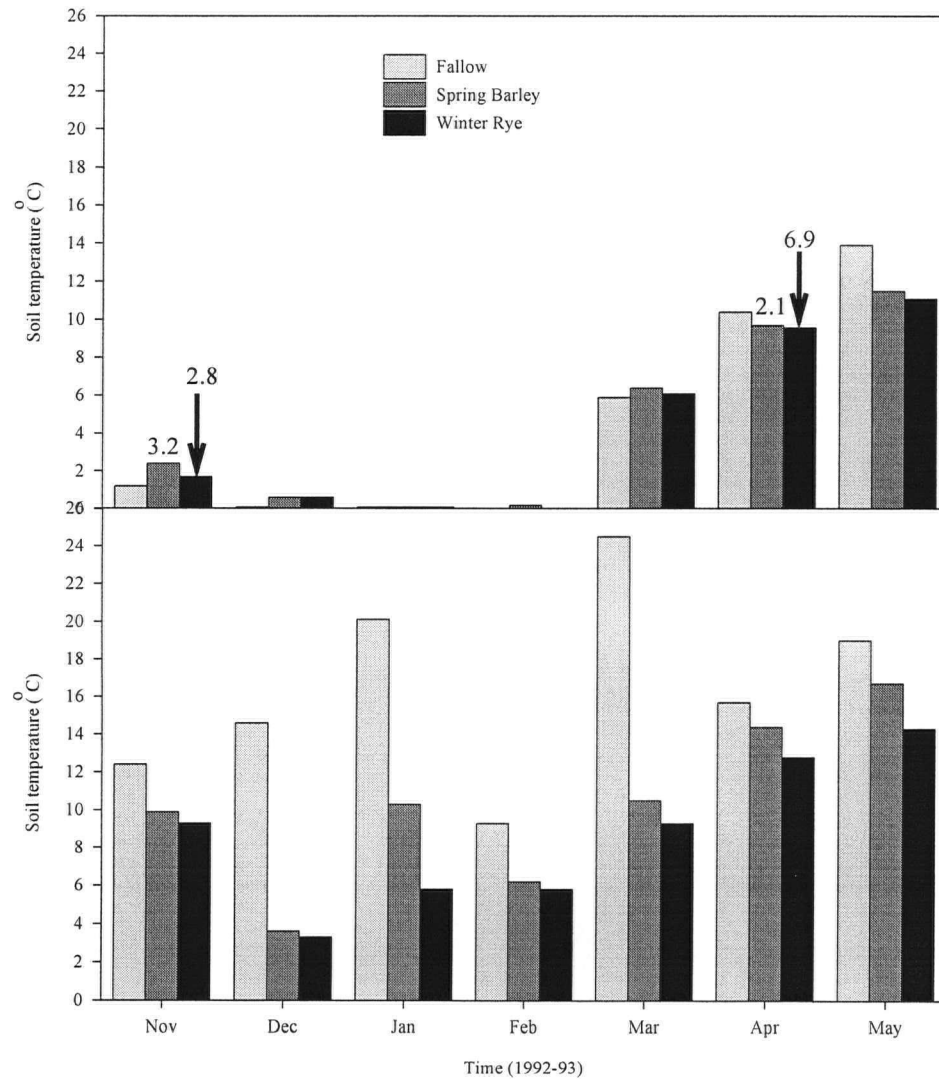
Figure 4-11. Monthly minimum (above) and maximum (below) soil temperatures at 3 cm depth during the 1992-93 winter cropping season (values above the bars for spring barley and winter rye represent averages over the N treatment of the amount of cover in t ha⁻¹).
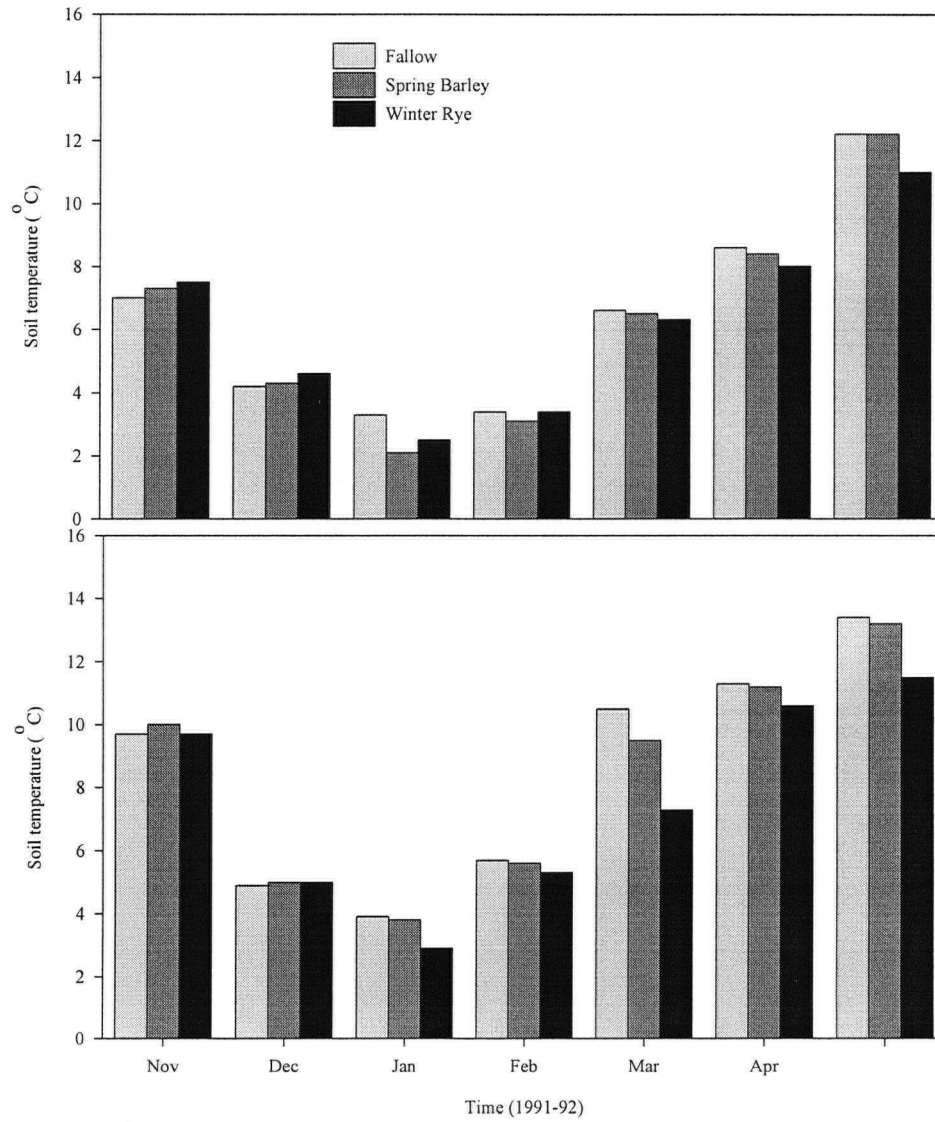
Figure 4-12. Monthly minimum (above) and maximum (below) soil temperatures at 40 cm depth during the 1992-93 winter cropping season.

Chapter 5: RESULTS

5-1. DYNAMICS OF AUTUMN SOIL MINERAL NITROGEN

5-1.1. Soil mineral nitrogen status in fallow plots

Soil mineral N (NH_4^+ + NO_3^-) content in the 0-60 cm layer for the three seasons, determined on samples taken before planting of cover crops in August and September, was variable among the three locations (L91, L92 and L93) and between the two planting dates (Table 5-1).

Table 5-1. Main growing season residual soil mineral N for samples taken immediately before planting in the three cover cropping seasons.

Sampling date	N level	Soil sampling depth intervals (cm)			
		0-20	20-40	40-60	0-60
		.... ($kg\ ha^{-1}$)			
August/19/1991	N-0	64	30	30	124
	N-100‡	164	30	30	224
September/16/1991	N-0	58	53	36	148
	N-100	113	89	43	245
August/24/1992	N-0	38	18	18	74
	N-100‡	138	18	18	174
September/22/1992	N-0	46	21	23	90
	N-100	153	22	25	200
August/24/1993	N-0	96	61	38	196
	N-100‡	196	61	38	296

N-0, autumn residual mineral N only; N-100, autumn residual mineral N + 100 kg N ha^{-1} as NO_3^-; ‡ Theoretical sum of amount determined before N application and 100 kg N ha^{-1} added after planting;

Changes in soil mineral N (0-60 cm layer) in fallow plots that received no fertilizer N at planting for the three winter cropping seasons are shown in Figure 5-1. At the beginning of the seasons, a higher proportion of the N was in the surface 20 cm and decreased gradually with depth.
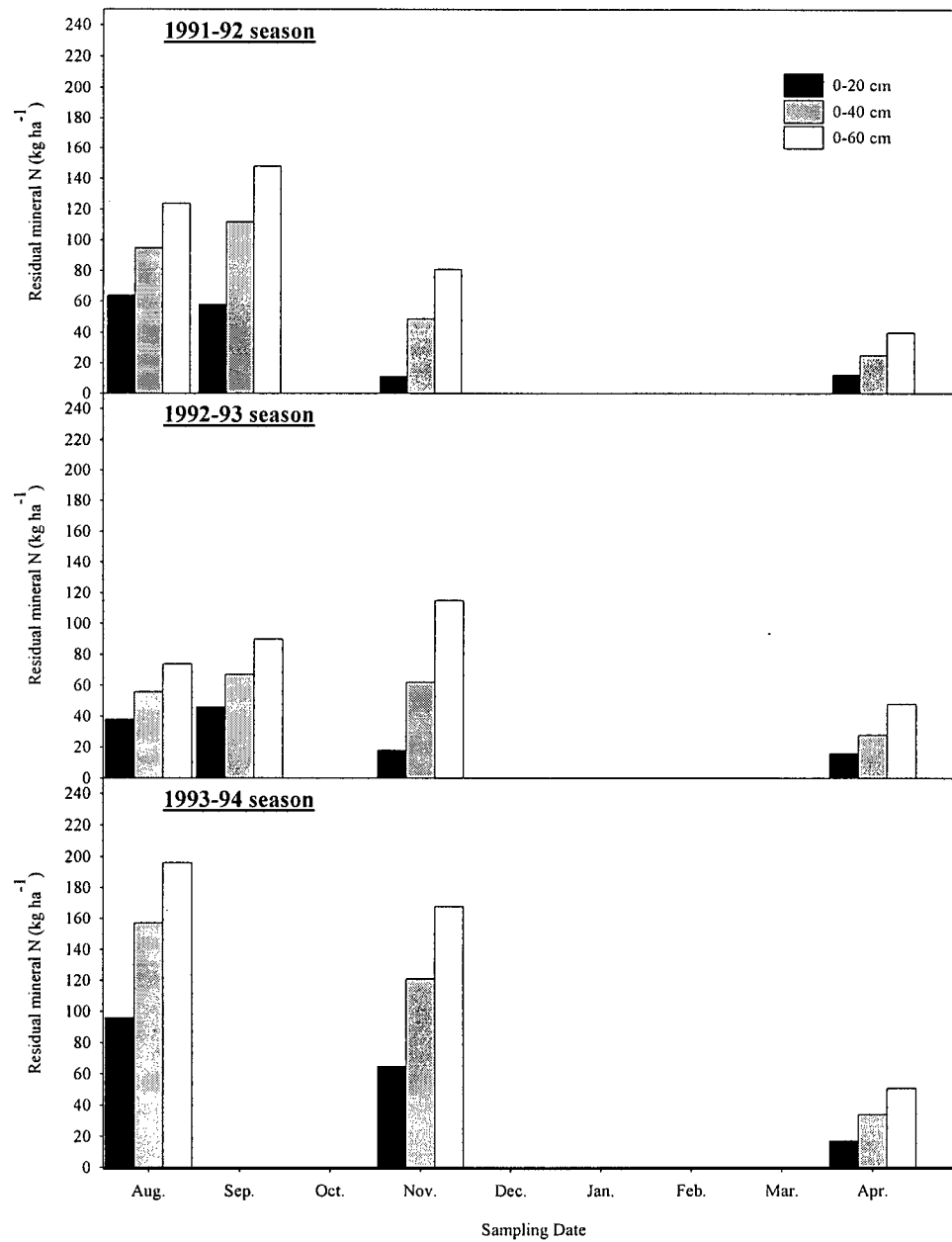
Figure 5-1. Temporal pattern of changes in soil mineral N in the 0-60 cm layer in fallow plots at the primary level (N-0) of autumn soil mineral N for the three winter cropping seasons.

Soil N mineralization from organic matter was evident at the late planting date (September) at the 1991 location (L91) and up to November at the 1992 location (L92). At both locations, soil mineral N content in late November increased with depth, indicating the start of leaching. In late November 1993, soil mineral N content gradually decreased down the profile, indicating NO_3^- leaching into the subsurface layers was minor. At all three locations (L91, L92 and L93), the least amount of mineral N was measured in the spring and generally increased with depth. Soil mineral N decrease in fallow plots (N-0) in the 0-60 cm layer between late November and April of 1991-92, 1992-93 and 1993-94 winter seasons was 51, 59 and 70% (of that measured in November), respectively.

5-1.2. Cover crop biomass and nitrogen before winter leaching period

The effects of planting date, autumn soil mineral N content and crop species on biomass production and N uptake before winter leaching period for 1991-92 and 1992-93 seasons are summarized in Tables 5-2 and 5-3, respectively. At the start of 1991 and 1992 winter seasons (late November), variability in cover crop biomass production and N uptake were independent of crop species but were largely due to planting date and autumn soil mineral N content. In late November 1991, planting of cover crops in the third week of August as compared to a month later increased cover crop biomass production by 135% and N uptake by 38%. Similarly, increasing autumn soil mineral N content by 100 kg ha^{-1} increased cover crop productivity by 28% and N uptake by 41%. In late November 1992, cover crop biomass production and N uptake increased with increase in autumn soil mineral N content when cover crops were planted in August but changed little when planted a month later (Figure 5-2). When averaged over cover crops, biomass and N content of August-planted cover crops increased by 56 and 93%, respectively, with increasing autumn soil N content; the average biomass of September-planted

cover crops was not influenced by soil mineral N content and N uptake increased by only 9%. In both years, autumn-planted spring barley was not different from winter rye in terms of productivity and capturing main-growing-season residual mineral N before winter leaching period. Maximum N uptake capacity averaged 95 and 107 kg ha^{-1} in late November 1991 and 1992, respectively, and occurred when cover crops were planted in August.

Table 5-2. Effect of planting date, autumn soil nitrogen content and crop species on biomass and cover crop N before winter leaching period (November 21, 1991).

Treatment	Biomass	Cover crop N
	Mean values¶	
Planting date		
August/19/1991	4.0	95
September/16/1991	1.7	69
Nitrogen level		
N-0	2.5	68
N-100	3.2	96
	Treatment effects (P > F values)	
Planting date (D)	0.0024	0.0460
Nitrogen (N)	0.0325	0.0144
D x N	NS	NS
Cover crop (C)	NS	NS
C x D	NS	NS
C x N	NS	NS
C x D x N	NS	NS
CV (%)	25	35

¶ Biomass is expressed as t ha^{-1} and cover crop N as kg ha^{-1}; NS, not significant (P > 0.05);

Table 5-3. Effect of planting date, autumn soil mineral nitrogen content and crop species on biomass and cover crop N before winter leaching period (November 24, 1992).

Treatment	Biomass	Cover crop N
	Mean values¶	
Planting date		
August/24/1992	3.0	107
September/22/1992	1.0	48
Nitrogen level		
N-0	1.7	59
N-100	2.3	95
	Treatment effects (P > F values)	
Planting date (D)	0.0007	0.0017
Nitrogen (N)	0.0021	0.0001
D x N	0.0022	0.0002
Cover crop (C)	NS	NS
C x D	NS	NS
C x N	NS	NS
C x D x N	NS	NS

¶ Biomass is expressed as t ha^{-1} and cover crop N as kg ha^{-1}; NS, not significant (P > 0.05);
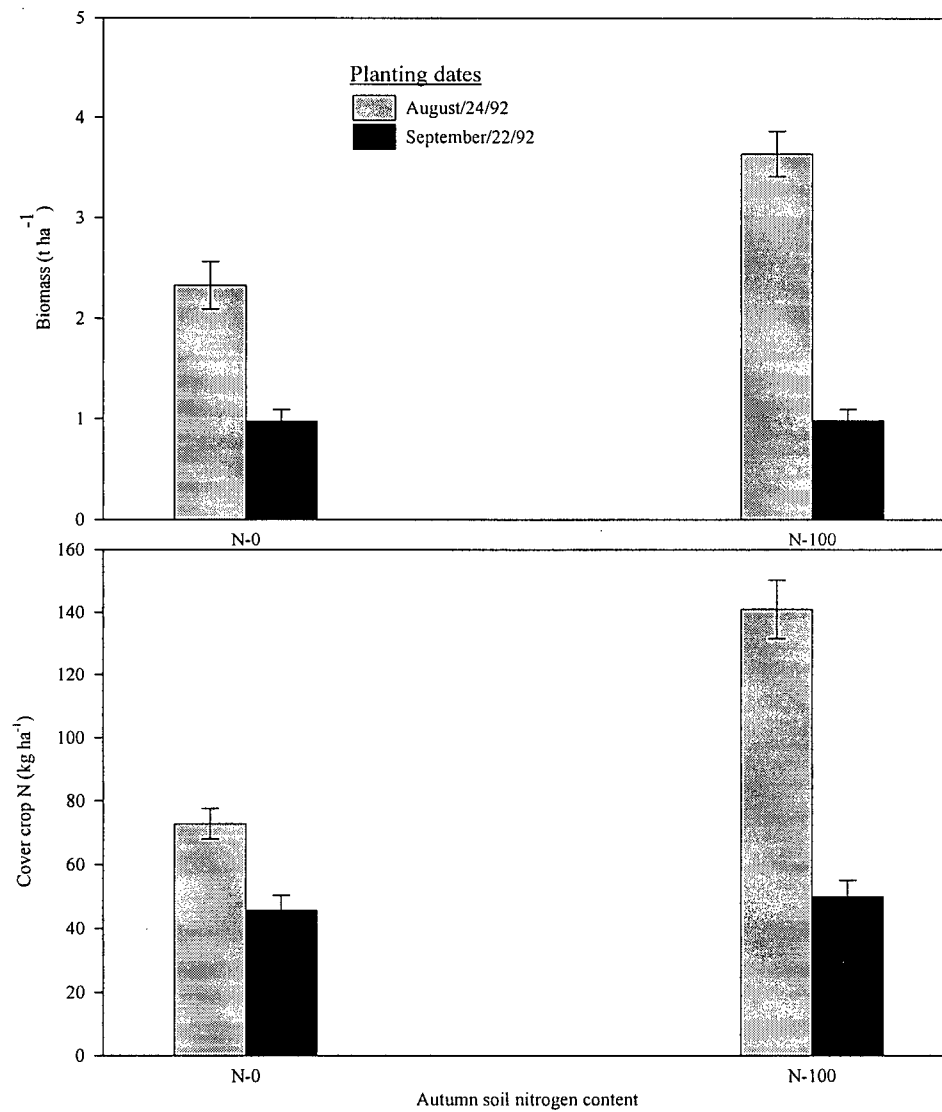
Figure 5-2. Biomass production (above) and N uptake (below) of autumn-planted spring barley and winter rye before winter leaching period (November 24, 1992) as influenced by planting date and autumn soil mineral N content. Error bars represent standard error of the mean (n = 8).

In the 1993-94 winter cropping season all crops were planted on August 24, 1993, the date that represented early planting in the previous two seasons. Fallow plots were heavily infested with chickweed (*Stellaria media* L.) and thus a bare control was not maintained. Variations in cover crop biomass production and N uptake before winter leaching period were mainly due to crop species (Table 5-4).

Table 5-4. Effect of autumn soil mineral nitrogen content and cover crop species on biomass production and cover crop N before winter leaching period (November 24, 1993).

Treatment	Biomass	Cover crop N
	Mean values¶	
Crop species		
Fallow/Chickweed (F)	2.8	89
Spring barley (SB)	4.2	115
Spring wheat (SW)	5.4	157
Spring oat (SO)	5.3	142
Winter rye (WR)	3.7	144
Annual ryegrass (ARG)	4.3	146
	Treatment effects (P > F values)	
Nitrogen (N)	NS	NS
Cover crop (C)	0.0001	0.0001
C x N	NS	NS
CV (%)	10	14
	Orthogonal contrasts for cover crop	
F vs SB+SW+SO+WR+ARG	0.0001	0.0019
SB vs SW+SO	0.0001	0.0001
SW vs SO	NS	NS
WR vs ARG	0.0040	NS
SB+SW+SO vs WR+ARG	0.0001	0.0045

¶ Biomass is expressed as t ha^{-1} and cover crop N as kg ha^{-1}; NS, not significant (P > 0.05);

Generally, cover crop biomass production and N accumulation were greater relative to those of chickweed in fallow plots. Among spring species, wheat and oat produced greater biomass and took up more mineral N when compared with barley. In contrast, annual ryegrass produced greater biomass than winter rye but the two cover crops were similar in terms of N uptake. A general statistical contrast analysis of spring species with winter species indicates that despite significantly less biomass production than that for spring species, winter species absorbed relatively greater amounts of residual mineral N.

5-1.3. Soil mineral nitrogen content before winter leaching period

The influence of planting date, autumn soil mineral N content and crop species on residual mineral N in the 0-60 cm layer varied greatly among the three years. In late November 1991, variations in soil mineral N content were not influenced by planting date but were independently affected by early autumn soil mineral N content and crop species (Table 5-5). The main effect of the N treatment indicated that, on average, a significant proportion (47%) of fertilizer N was recovered in the 0-60 cm layer before winter leaching period. When averaged over planting date and autumn soil N content, spring barley and winter rye reduced soil mineral N by 53 and 54%, respectively. In contrast, planting date, autumn soil mineral N content and crop species influenced soil mineral N in late November 1992 (Table 5-6). Residual soil mineral N under autumn-planted spring barley and winter rye increased with delay in planting but a greater increase occurred under winter rye than spring barley (Figure 5-3). Residual mineral N under winter rye and spring barley increased by 246 and 87%, respectively, when planting was delayed by one month. The data shows that planting of winter rye in August

Table 5-5. Effect of planting date, autumn soil nitrogen content and cover crop species on residual soil mineral N before winter leaching period (November 21, 1991)

Treatment	Soil sampling depth intervals (cm)		
	0-20	0-40	0-60
	Mean values (kg ha^{-1})		
Nitrogen level			
N-0	10	30	51
N-100	19	56	98
Crop species			
Fallow (F)	13	65	116
Spring Barley (SB)	20	36	55
Winter Rye (WR)	11	28	53
	Treatment effects (P > F values)¶		
Planting date (D)	NS	NS	NS
Nitrogen (N)	0.0048	0.0007	0.0001
D x N	NS	NS	NS
Cover crop (C)	0.0047	0.0001	0.0001
C x D	NS	NS	NS
C x N	NS	NS	NS
C x D x N	NS	NS	NS
CV (%)	16	8	6
	Orthogonal contrasts for cover crop		
F vs SB + WR	0.0018	0.0060	0.0001
SB vs WR	NS	0.0001	0.0001

¶Analysis of variance performed on data transformed to natural logarithm scale; NS, not significant (P < 0.05);

Table 5-6. Effect of planting date, autumn soil mineral nitrogen content and crop species on residual soil mineral N before winter leaching period (November 24, 1992).

Treatment	Soil sampling depth intervals (cm)		
	0-20	0-40	0-60
	Mean values (kg ha^{-1})		
Nitrogen level			
N-0	39	72	102
N-100	79	120	152
Crop species			
Fallow/chickweed	84	146	194
Spring barley	53	90	121
Spring wheat	51	88	116
Spring oat	63	97	123
Winter rye	58	80	102
Annual ryegrass	44	74	106
	Treatment effects (P > F values)¶		
Planting date (D)	NS	0.0238	0.0261
Nitrogen (N)	0.0027	0.0013	0.0024
D x N	NS	NS	NS
Cover crop (C)	0.0001	0.0001	0.0001
C x D	NS	0.0001	0.0001
C x N	0.0381	0.0132	0.0223
C x D x N	NS	NS	NS
CV (%)	11	5	4
	Orthogonal contrasts for cover crop and interactions		
F vs SB+WR	NS	0.0075	0.0046
SB vs WR	0.0001	0.0001	0.0001
(F vs SB+WR)x(D1 vs D2)	NS	NS	NS
(SB vs WR)x(D1 vs D2)	NS	0.0001	0.0001
(F vs SB+WR)x(N1 vs N2)	NS	NS	NS
(SB vs WR)x(N1 vs N2)	NS	0.0078	0.0079

¶ Analysis of variance performed on data transformed to natural logarithm scale; F = fallow; SB = spring barley; WR = winter rye; NS, not significant (P < 0.05);
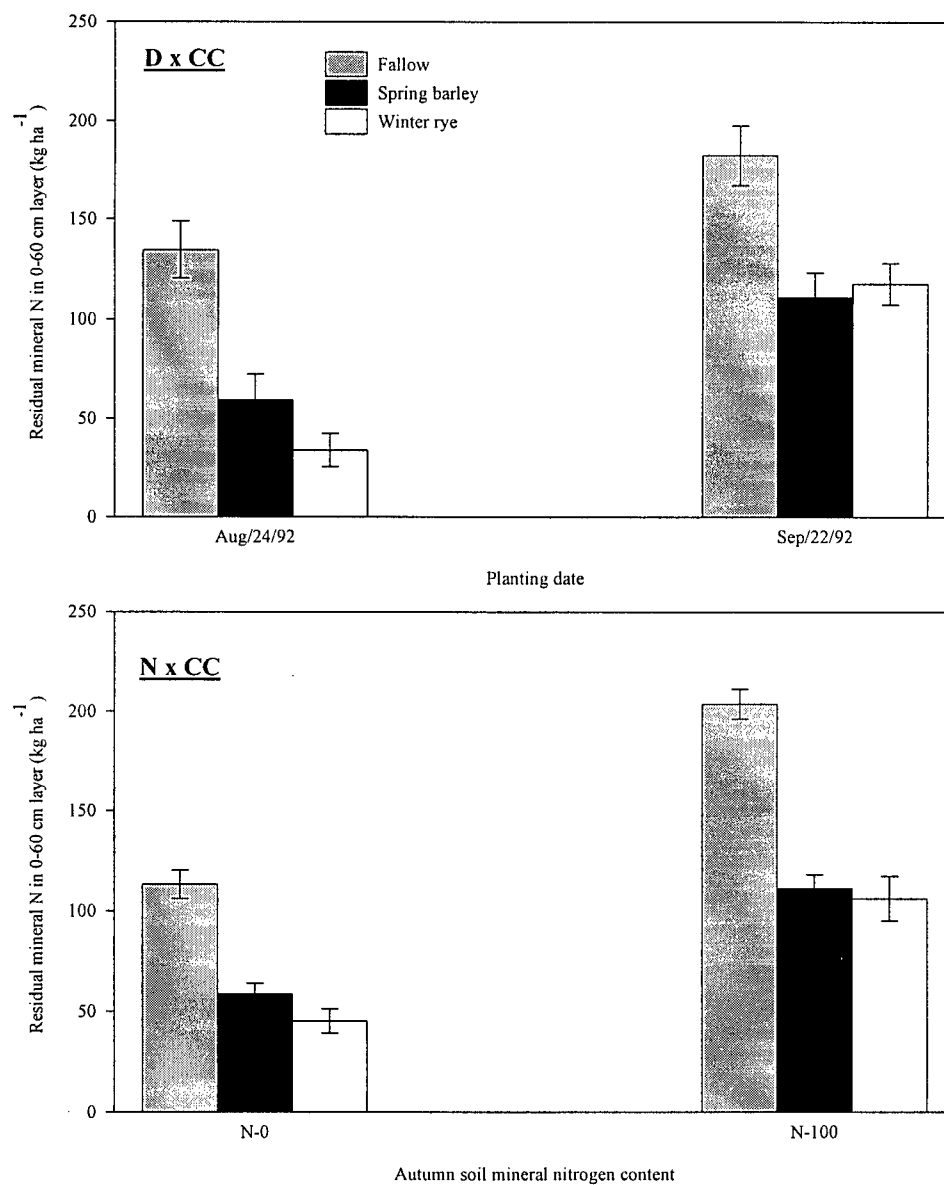
Figure 5-3. Variations in residual mineral N in the 0-60 cm layer in late November 1992 under fallow, spring barley and winter rye as influenced by planting date (above) and, autumn soil N content (below). Error bars represent standard error of the mean (n = 8). D x CC = planting date x crop species interaction; N x CC = nitrogen x crop species interaction;

caused greater reduction in soil mineral N than spring barley but the two cover crops were not different when planted a month later. Similarly, residual mineral N increase under winter rye and spring barley was 91 and 136%, respectively, when an additional 100 kg N ha^{-1} was applied. The data indicates that under low N supply, winter rye resulted in greater soil mineral N reduction than spring barley but that the two cover crops were comparable when an additional 100 kg N ha^{-1} was applied.

On average, significant proportions (47 to 75%) of applied fertilizer N were recovered (ANR$_{soil}$) in the 0-60 cm soil layer in late November in all the three years. Generally, the proportions recovered increased sharply with depth in late November 1991 but gradually decreased with depth in late November 1992. This suggested substantial downward movement of NO$_3^-$ in both years. In contrast, the proportions of fertilizer N recovered in 1993 decreased sharply with depth, indicating little movement into the subsurface layers.

In late November 1993, variations in residual mineral N were dependent on autumn soil mineral N content and crop species (Table 5-7). When averaged over the N treatment, cover cropping reduced soil mineral N by 42% in the 0-60 cm soil layer, despite considerable chickweed (*Stellaria media* L.) growth on fallow plots. Corresponding reduction in soil NO$_3^-$ was 47% in the 0-60 cm layer. This is not surprising as cover crops generally accumulated greater amounts of soil mineral N compared to chickweed by November 24, 1993 (see Table 5-4). The data also indicates that spring wheat was more effective in reducing soil mineral N in the 0-40 cm layer than spring oat when 100 kg ha^{-1} was applied (Figure 5-4.).

Table 5-7. Effect of autumn soil mineral nitrogen content and crop species on residual mineral N before winter leaching period (November 24, 1993).

Treatment	Soil sampling depth intervals (cm)		
	0-20	0-40	0-60
	Mean values (kg ha^{-1})		
Nitrogen level			
N-0	39	72	102
N-100	79	120	152
Crop species			
Fallow/Chickweed (F)	84	146	194
Spring Barley (SB)	53	90	121
Spring Wheat (SW)	51	88	116
Spring oat (SO)	63	97	123
Winter Rye (WR)	58	80	102
Annual Ryegrass (ARG)	44	74	106
	Treatment effects (P > F values)¶		
Nitrogen (N)	0.0065	0.0132	0.0039
Cover crop (C)	0.0001	0.0001	0.0001
C x N	0.0007	0.0324	NS
CV (%)	6	4	4
	Orthogonal contrasts for cover crop and interactions		
F vs SB+SW+SO+WR+ARG	0.0001	0.0001	0.0001
SB vs SW+SO	NS	NS	NS
SW vs SO	0.0034	NS	NS
WR vs ARG	NS	NS	NS
SB+SW+SO vs WR+ARG	NS	NS	NS
(F vs SB+SW+SO+WR+ARG)x(N1xN2)	0.0447	NS	NS
(SB vs SW+SO)x(N1xN2)	NS	NS	NS
(SW vs SO)x(N1xN2)	0.0001	0.0039	NS
(WR vsARG)x(N1xN2)	NS	NS	NS
(SB+SW+SO vs WR+ARG)x(N1xN2)	NS	NS	NS

¶Analysis of variance performed on data transformed to natural logarithm scale; N1 = N-0; N2 = N-100; NS, not significant (P > 0.05);
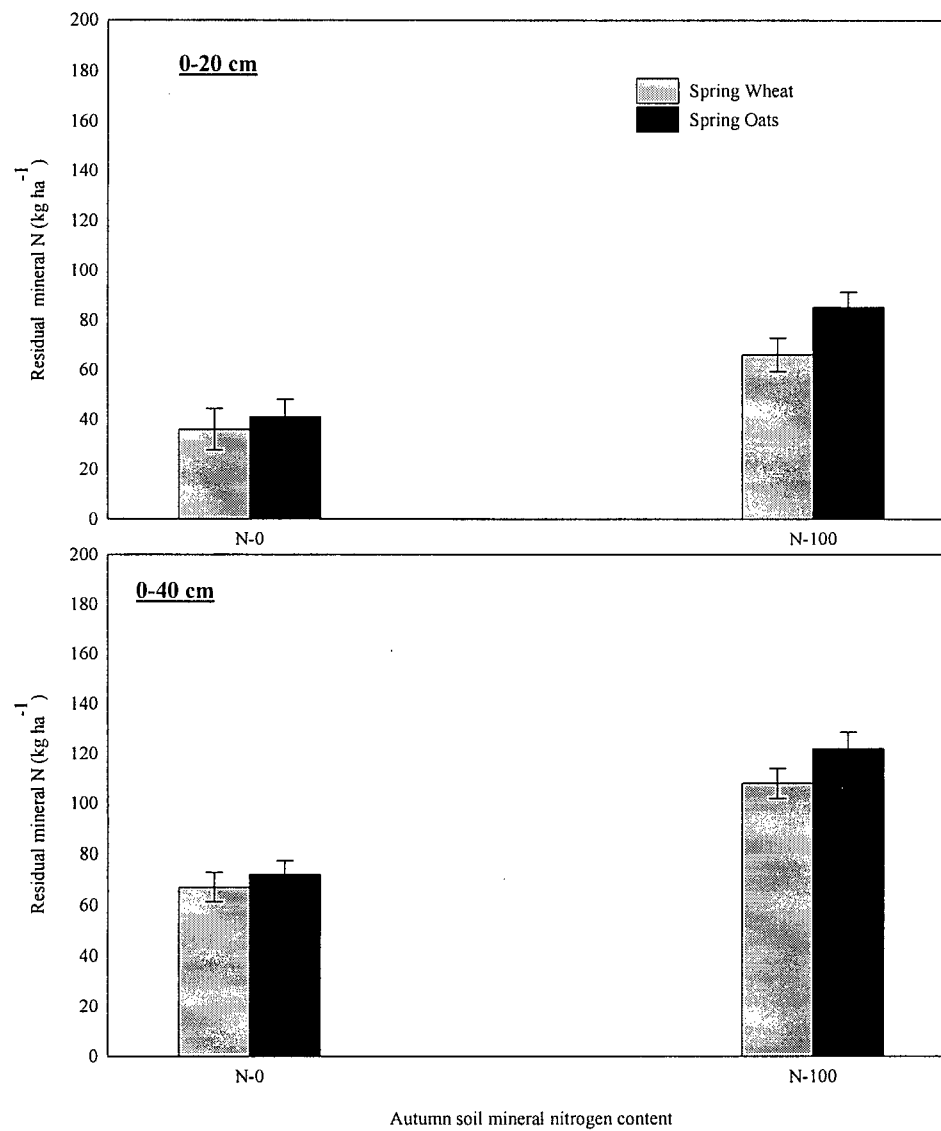
Figure 5-4. Variations in residual mineral N in late November 1993 in the 0-20 (above) and 0-40 cm layers under spring wheat and spring oat as influenced by autumn soil nitrogen content. Error bars represent standard error of the mean (n = 4).

5-1.4. Impact of cover cropping on soil NO₃⁻ before winter leaching period

Table 5-8 shows that percent NO_3^- reduction due to cover cropping was significantly influenced by planting date and crop species in late November 1992 and by crop species in 1993. The trend for the 1992 data indicates that when cover crops were planted in August, winter rye was more efficient than spring barley in reducing soil NO_3^- levels in the 0-60 cm layer before winter leaching period but when planted one month later the two cover crops were equally less effective (Figure 5-5). Before winter leaching period of 1993, winter rye, annual ryegrass and spring wheat had comparable impact on soil NO_3^- content in the 0-60 cm layer but winter rye was more effective than either spring barley or spring oat (Table 5-9).

Table 5-8. Analysis of variance (P > F values) for planting date (D), autumn soil mineral nitrogen content (N) and crop species effects on percent NO_3^--N reduction (PR) in the 0-60 cm layer before winter leaching period for the three winter cropping seasons.

Treatment	November/21/1991	November/24/1992	November/24/1993
D	NS	0.0017	-
N	NS	NS	NS
D x N	NS	NS	-
C	NS	0.0263	0.0248
C x D	NS	0.0384	-
C x N	NS	NS	NS
C x D x N	NS	NS	-
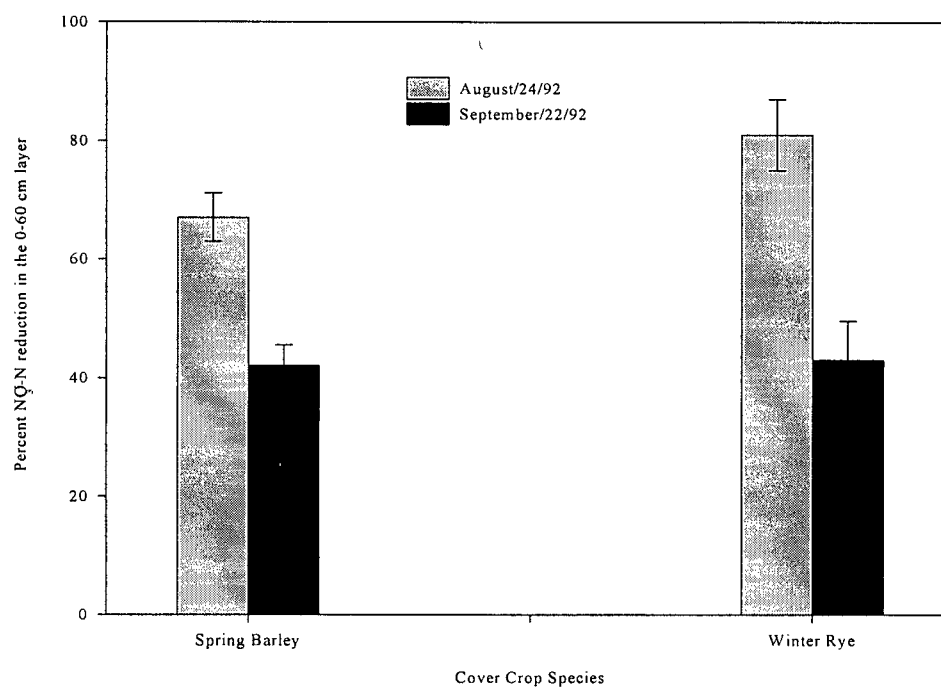
Figure 5-5. Influence of planting date on cover crop impact on soil NO$_3^-$ in the 0-60 cm layer before winter leaching period. Error bars represent standard error of the mean (n = 8).

Table 5-9. Influence of crop species on NO$_3^-$ reduction (% - PR) in the 0-60 cm layer before winter leaching period of 1993.

Crop species	NO$_3^-$ Reduction (%)
Spring barley	43b
Spring wheat	45ab
Spring oat	40b
Winter rye	57a
Annual ryegrass	53ab

5-1.5. Cover crop biomass and nitrogen after winter leaching period

In late November 1991, August- and September-planted spring barley winter-killed and August-planted winter rye was severely damaged by freezing. In contrast, only August-planted spring barley was killed by freezing in late November 1992 (Figure 5-6) and August-planted winter rye was damaged by freezing, especially where additional 100 kg N ha^{-1} was added (Figure 5-7). Cover crop biomass and N in the spring of 1992 were influenced by planting date and crop species (Table 5-10). The biomass of spring barley residue declined drastically (by 83% of that measured in November 1991) with delayed planting but that of winter rye increased (33%). Similarly, total N of spring barley residue decreased considerably (86%) with delayed planting but that of winter rye increased (42%) (Figure 5-8).

Table 5-10. Effect of planting date, autumn soil nitrogen content and crop species on biomass and cover crop N after winter leaching period (April 08, 1992).

Treatment	Biomass	Cover crop N
	Treatment effects (P > F values)	
Planting date (D)	NS	NS
Nitrogen (N)	NS	NS
D x N	NS	NS
Cover crop (C)	0.0001	0.0001
C x D	0.0111	0.0029
C x N	NS	NS
C x D x N	NS	NS
CV (%)	44	42

NS, not significant (P > 0.05);
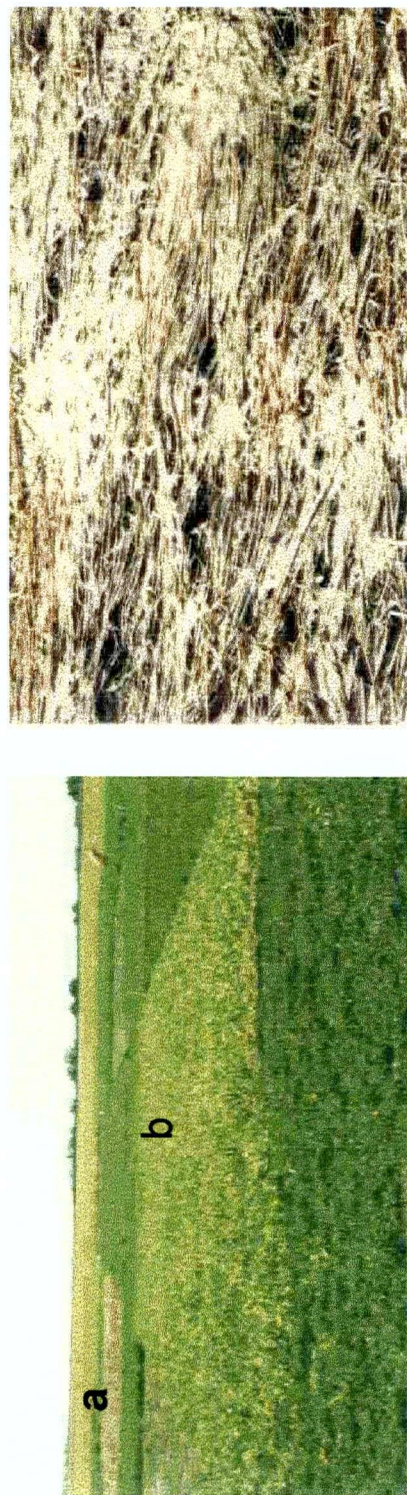
Figure 5-6 Photo showing winter-killed August-planted spring barley (a) and September-planted spring barley (b) in early tillering stage (left) and a close-up of spring barley mulch (right) on February 15, 1993 (right) [L.S. Nafuma].

Figure 5-7. Photo showing frost damage on August-planted winter rye that received 100 kg N ha^{-1} (left) and no N (right) at planting. [February 15, 1993 - L.S. Nafuma]
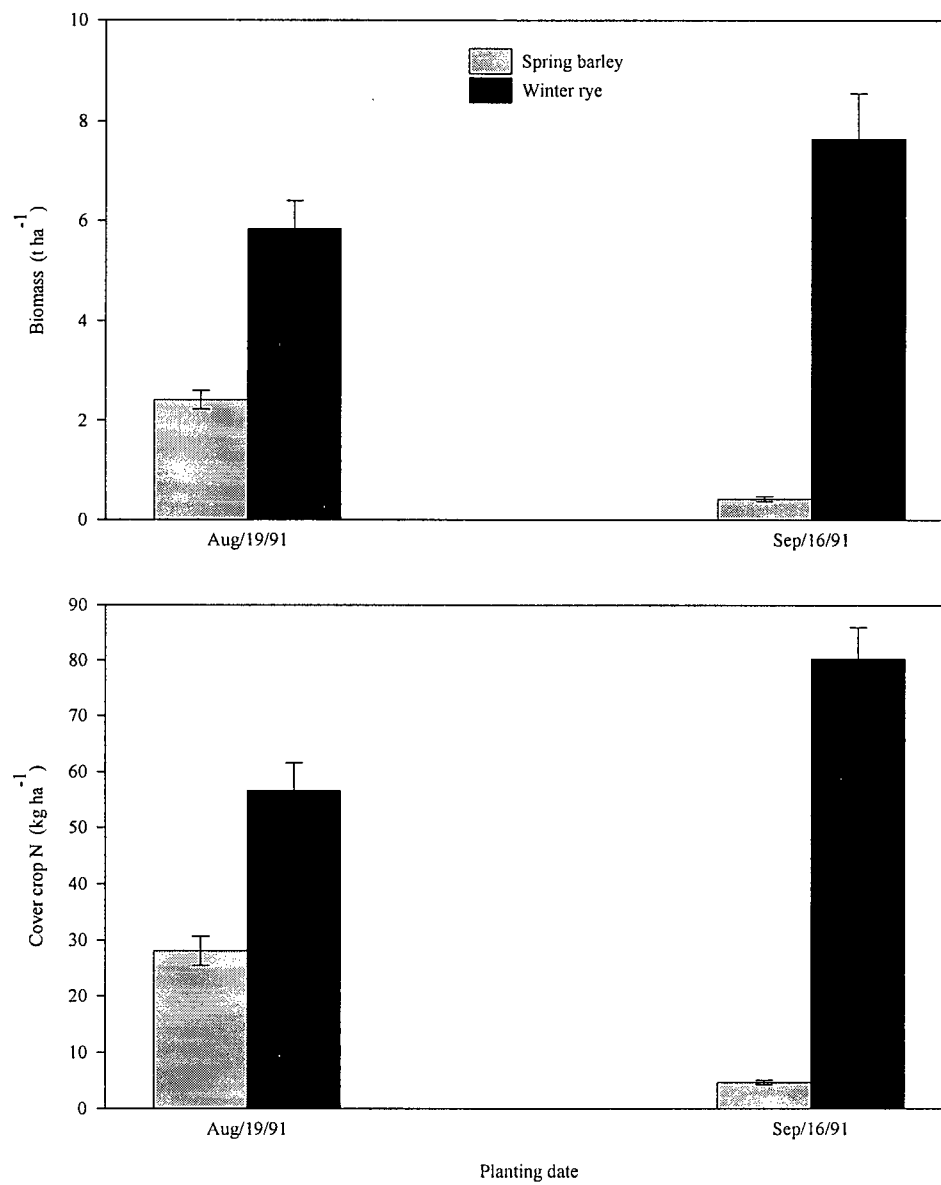
Figure 5-8. Spring barley and winter rye biomass (above) and nitrogen (below) in the spring of 1992. Error bars represent standard error of the mean (n = 8).

Effects of planting date, autumn soil mineral N content and crop species on biomass and cover crop N in the spring of 1993 are summarized in Table 5-11. The strong interaction between planting date and crop species indicates that the biomass of spring barley increased with delay in planting but that of winter rye decreased (Figure 5-9). Despite the fact that August-planted spring barley winter-killed in late November and all September-planted cover crops survived the winter, cover crop N increased with increase in autumn N supply when planted in August but was least affected when planted a month later (Figure 5-9).

Table 5-11. Effect of planting date, autumn soil mineral nitrogen content and cover crop species on biomass and cover crop N after winter leaching period (April 30, 1993).

Treatment	Biomass	Cover crop N
	Treatment effects (P > F values)	
Planting date (D)	NS	0.0297
Nitrogen (N)	0.0169	0.0006
D x N	NS	0.0157
Cover crop (C)	0.0001	0.0001
C x D	0.0006	NS
C x N	NS	NS
C x D x N	NS	NS
CV (%)	22	26

NS, not significant (P > 0.05);
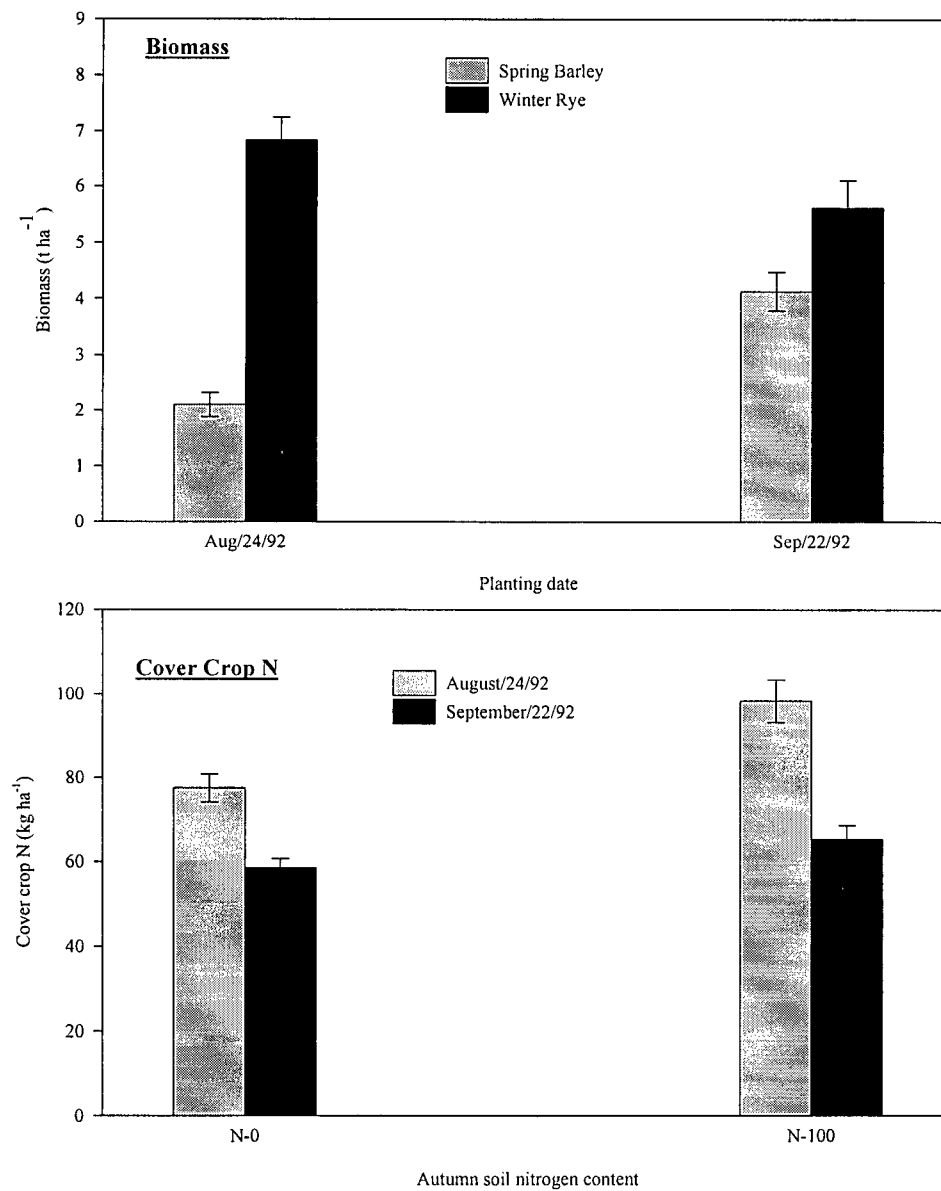
Figure 5-9. Spring barley and winter rye biomass (above) and nitrogen (below) in the spring of 1993 as influenced by planting date and autumn soil mineral N content. Error bars represent standard error of the mean (n = 8).

In the spring of 1994, variations in cover crop biomass and N were independent of autumn soil mineral N content but were mainly affected by crop species (Table 5-12). Generally, cover crop biomass and N were greater than those of chickweed in fallow plots, although spring species residue biomass and N averaged only 1.4 t ha^{-1} and 24 kg N ha^{-1}, respectively. A general comparison of winter species (winter rye and annual ryegrass) with autumn-planted spring species (barley, wheat and oat) showed that winter species had higher biomass and N relative to spring species.

Table 5-12. Effect of autumn soil mineral nitrogen content and cover crop species on biomass and cover crop N after winter leaching period (April 14, 1994).

Treatment	Biomass	Cover crop N
	Mean values¶	
Crop species		
Fallow/Chickweed (F)	3.4	60
Spring barley (SB)	1.6	27
Spring wheat (SW)	1.7	26
Spring oat (SO)	1.1	20
Winter rye (WR)	7.7	149
Annual ryegrass (ARG)	8.9	155
	Treatment effects (P > F values)	
Nitrogen (N)	NS	NS
Cover crop (C)	0.0001	0.0001
C x N	NS	NS
CV (%)	16	22
	Orthogonal contrasts for cover crop	
F vs SB+SW+SO+WR+ARG	0.0001	0.0001
SB vs SW+SO	0.0001	0.0001
SW vs SO	0.0005	NS
WR vs ARG	NS	NS
SB+SW+SO vs WR+ARG	0.0001	0.0001

¶ Biomass is expressed as t ha^{-1} and cover crop N as kg ha^{-1}; NS, not significant (P > 0.05);

5-1.6. Soil mineral nitrogen content after winter leaching period

The influence of planting date, autumn soil mineral N content and crop species on residual mineral N in the 0-60 cm layer in spring of 1992 and 1993 varied with years. Variations in residual mineral N in the spring of 1992 (Table 5-13) were influenced by autumn planting date and crop species in the 0-20 cm layer and by crop species at all depth intervals. When spring barley was planted in August a greater increase in mineral N in the surface 20 cm was observed compared to fallow or winter rye (Figure 5-10). However, when cover crops were planted in September, mineral N was not considerably influenced by crop species. The main effect of crop species shows that growth of autumn-planted spring barley increased mineral N relative to fallow or winter rye at all depths (0-20, 0-40 and 0-60 cm). In contrast, variations in residual mineral N in the spring of 1993 were influenced by planting date and crop species at all depth intervals (Table 5-14). Residual mineral N in August-planted spring barley plots increased when compared to that under fallow but decreased under September-planted cover crops (Figure 5-11). Variations in residual mineral N in the 0-60 cm layer in the spring of 1994 were largely due to crop species, especially in the subsurface soil layers (Table 5-15). Similar to the previous two seasons, greater amounts of soil mineral N were measured under autumn-planted spring species (barley, wheat and oat) residues than in fallow/chickweed or winter species (winter rye and annual ryegrass) plots.

Table 5-13. Effect of planting date, autumn soil nitrogen content and crop species on residual soil mineral N after winter leaching period (April 08, 1992).

	Soil sampling depth intervals (cm)		
Treatment	0-20	0-40	0-60
	Mean values (kg ha^{-1})		
Crop species			
Fallow (F)	14	25	42
Spring Barley (SB)	19	40	59
Winter Rye (WR)	12	22	32
	Treatment effects (P > F values)¶		
Planting date (D)	NS	NS	NS
Nitrogen (N)	NS	NS	NS
D x N	NS	NS	NS
Cover crop (C)	0.0056	0.0001	0.0001
C x D	0.0040	NS	NS
C x N	NS	NS	NS
C x D x N	NS	NS	NS
CV (%)	11	5	4
	Orthogonal contrasts for cover crop and interactions		
F vs SB+WR	0.0036	0.0001	0.0001
SB vs WR	NS	NS	0.0079
(F vs SB+WR) x (D1 vs D2)	0.0057	NS	NS
(SB vs WR) x (D1 vs D2)	0.0382	NS	NS

¶ Analysis of variance performed on data transformed to natural logarithm scale; NS, not significant (P < 0.05);
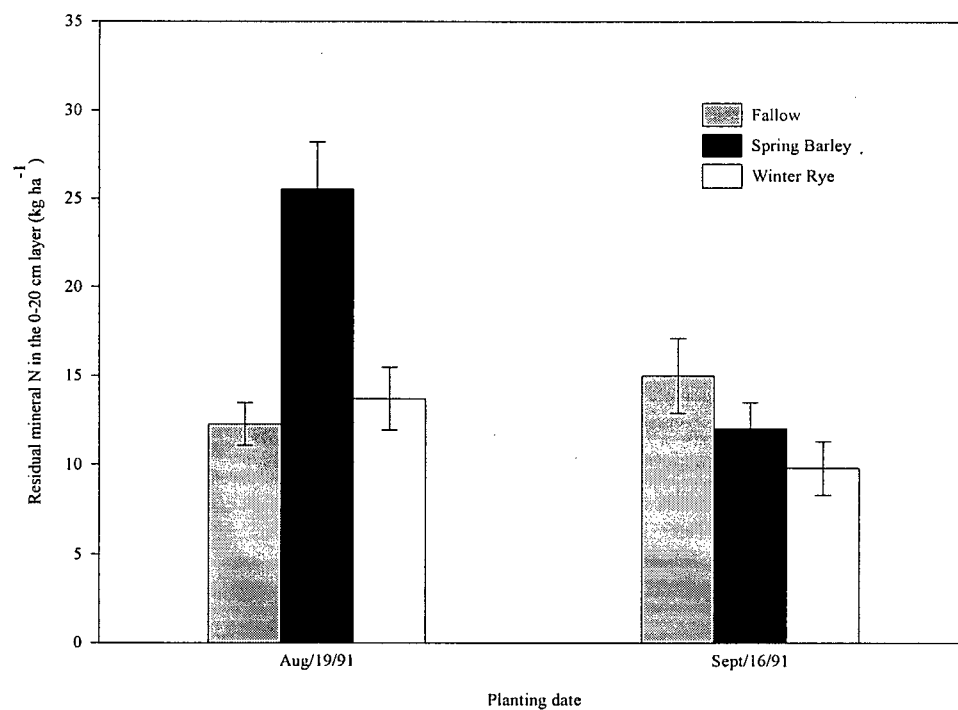
Figure 5-10. Soil mineral N in spring of 1992 in the 0-20 cm layer under fallow, spring barley and winter rye as influenced by planting date. Error bars represent standard error of the mean (n = 8).

Table 5-14. Effect of planting date, autumn soil mineral nitrogen content and crop species on residual soil mineral N after winter leaching period (April 30, 1993).

Treatment	Soil sampling depth intervals (cm)		
	0-20	0-40	0-60
	Mean values (kg ha^{-1})		
Planting date			
August/24/1992	19	39	62
September/22/1992	13	25	45
Nitrogen level			
N-0	14	28	45
N-100	17	36	63
Crop species			
Fallow (F)	18	33	62
Spring Barley (SB)	18	40	65
Winter Rye (WR)	12	23	34
	Treatment effects (P > F values)¶		
Planting date (D)	NS	0.0330	0.0390
Nitrogen (N)	NS	0.0355	0.0091
D x N	NS	NS	NS
Cover crop (C)	0.0001	0.0001	0.0001
C x D	0.0028	0.0001	0.0001
C x N	NS	NS	NS
C x D x N	NS	NS	NS
CV (%)	9	6	5
	Orthogonal contrasts for cover crop and interactions		
F vs SB+WR	0.0172	0.0001	0.0001
SB vs WR	0.0001	0.0001	0.0001
(F vs SB+WR) x (D1 vs D2)	0.0116	0.0001	0.0001
(SB vs WR) x (D1 vs D2)	0.0105	0.0053	0.0045

¶ Analysis of variance performed on data transformed to natural logarithm scale; NS, not significant (P < 0.05);
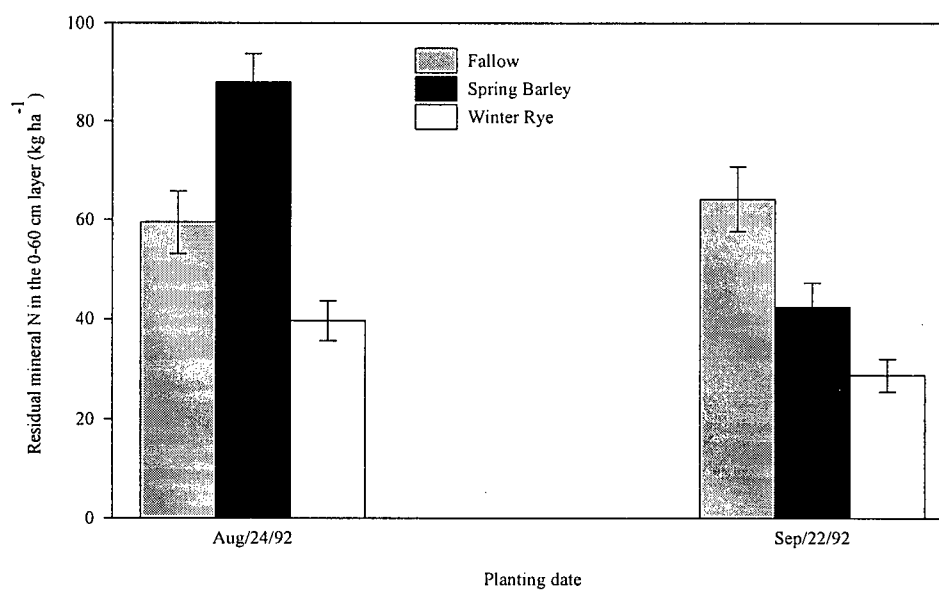
Figure 5-11. Soil mineral N in spring of 1993 in the 0-60 cm layer under fallow, spring barley and winter rye as influenced by planting date. Error bars represent standard error of the mean (n =8).

Table 5-15. Effect of autumn soil mineral nitrogen content and crop species on residual mineral N after winter leaching period (April 14, 1994).

Treatment	Soil sampling depth intervals (cm)		
	0-20	0-40	0-60
	Mean values (kg ha^{-1})		
Crop species			
Fallow/Chickweed (F)	18	34	54
Spring Barley (SB)	22	55	95
Spring Wheat (SW)	17	48	84
Spring oat (SO)	19	47	84
Winter Rye (WR)	19	33	45
Annual Ryegrass (ARG)	15	27	41
	Treatment effects (P > F values)¶		
Nitrogen (N)	NS	NS	NS
Cover crop (C)	NS	0.0001	0.0001
C x N	NS	NS	NS
CV (%)	10	5	5
	Orthogonal contrasts for cover crop and interactions		
F vs SB+SW+SO+WR+ARG	NS	0.0001	0.0001
SB vs SW+SO	NS	0.0287	0.0045
SW vs SO	NS	0.0113	NS
WR vs ARG	NS	NS	NS
SB+SW+SO vs WR+ARG	NS	0.0001	0.0001

¶Analysis of variance performed on data transformed to natural logarithm scale; NS, not significant (P > 0.05);

5-1.7. Changes in cover crop biomass and nitrogen during winter

A summary of statistical significance of biomass and cover crop N during the 1991-92, 1992-93 and 1993-94 winter cropping seasons is shown in Table 5-16.

Table 5-16. Repeated measures analysis of variance (P > F values) for planting date (D), autumn soil nitrogen content (N), crop species (C) and time of sampling (T) effects on variations in biomass and cover crop N during the three cropping winters.

Treatment	Biomass	Cover crop N
	.... (P > F values)...................	
	1991-92	
T	0.0092	0.0002
T x D	0.0186	NS
T x N	NS	NS
T x D x N	NS	NS
T x C	0.0001	0.0125
T x C x D	0.0214	0.0366
T x C x N	NS	NS
T x C x D x N	NS	NS
	1992-93	
T	0.0001	NS
T x D	0.0001	0.0018
T x N	NS	0.0200
T x D x N	0.0238	0.0109
T x C	0.0001	0.0024
T x C x D	0.0001	0.0307
T x C x N	NS	NS
T x C x D x N	NS	NS
	1993-94	
T	NS	0.0001
T x N	NS	NS
T x C	0.0001	0.0001
T x C x N	NS	NS

The three-way interaction (1991-92 season) between time of sampling (T), planting date (D) and crop species (C) indicates that the biomass of spring barley decreased during winter but that of winter rye increased, and that the changes were dependent on planting date (Figure 5-12). The decrease in biomass for August-planted spring barley during winter was 41% and for the September-planted cover crop was 75%. In contrast, biomass increase during winter for August- and September-planted winter rye were 51 and 345%, respectively. Spring barley and August-planted winter rye N that was accumulated before late November, decreased during winter but that for September-planted cover crop increased.

Similar variations in biomass and cover crop N with respect to time of sampling, planting date and crop species were observed in the 1992-93 winter cropping season (Table 5-16) and indicates the biomass for August-planted spring barley decreased by 34% during winter but that for September-planted crop increased by 459%. On the other hand, winter rye biomass increased during winter by 146 and 368% for the August- and September-planted crop, respectively (Figure 5-13). Cover crop N for August-planted spring barley decreased by 42% during winter but for the September-planted cover crop increased by only 22%. In contrast, N content of winter rye increased by 7 and 35% for the August- and September-planted cover crop, respectively.

Variations in biomass and cover crop N during 1993-94 winter were affected by time of sampling and crop species (Table 5-16). The biomass for autumn-planted spring barley, spring wheat and spring oat decreased between November 24, 1993 and April 14, 1994 by 63, 69 and 80%, respectively. In contrast, the biomass for chickweed (in fallow plots), winter rye and annual ryegrass increased by 24, 109 and 106%, respectively, within the 20-week period (Figure 5-14).
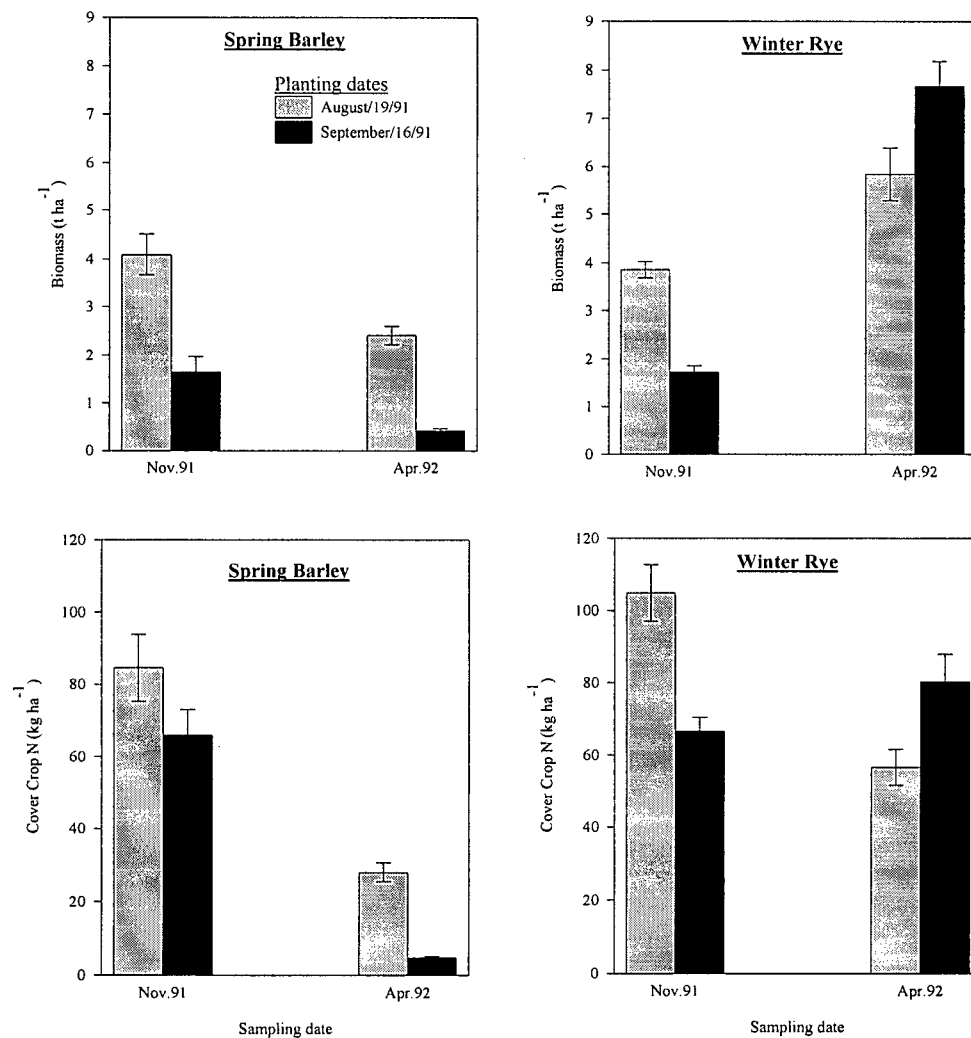
Figure 5-12. Changes in biomass (above) and cover crop N (below) during 1991-92 winter as influenced by planting date and crop species. Error bars represent standard error of the mean (n = 8).
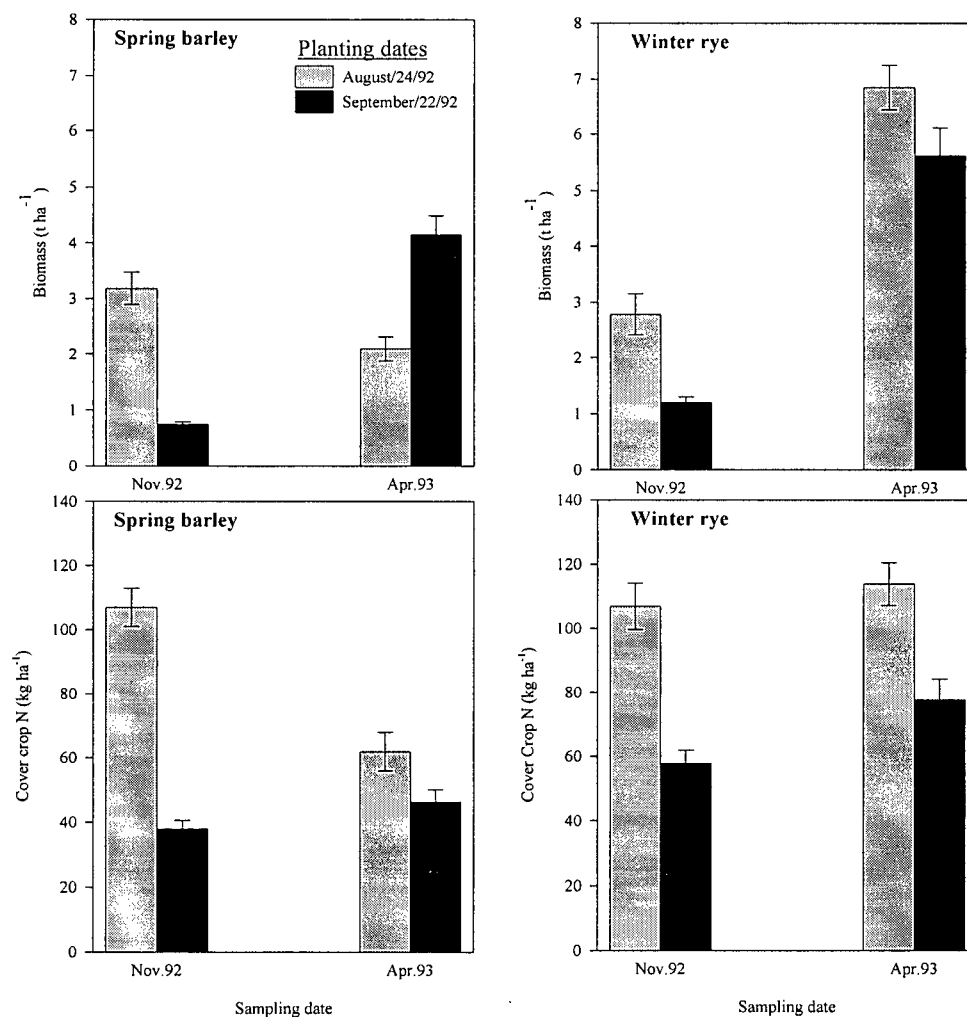
Figure 5-13. Changes in biomass (above) and cover crop N (below) during 1992-93 winter season as influenced by planting date and crop species. Error bars represent standard error of the mean (n = 8).

Nitrogen accumulated by spring barley, spring wheat and spring oat prior to winter declined by

76, 84 and 86%, respectively. The increase in cover crop N between late November 1993 and

April 1994 averaged only 4% for winter rye and annual ryegrass (Figure 5-14.).
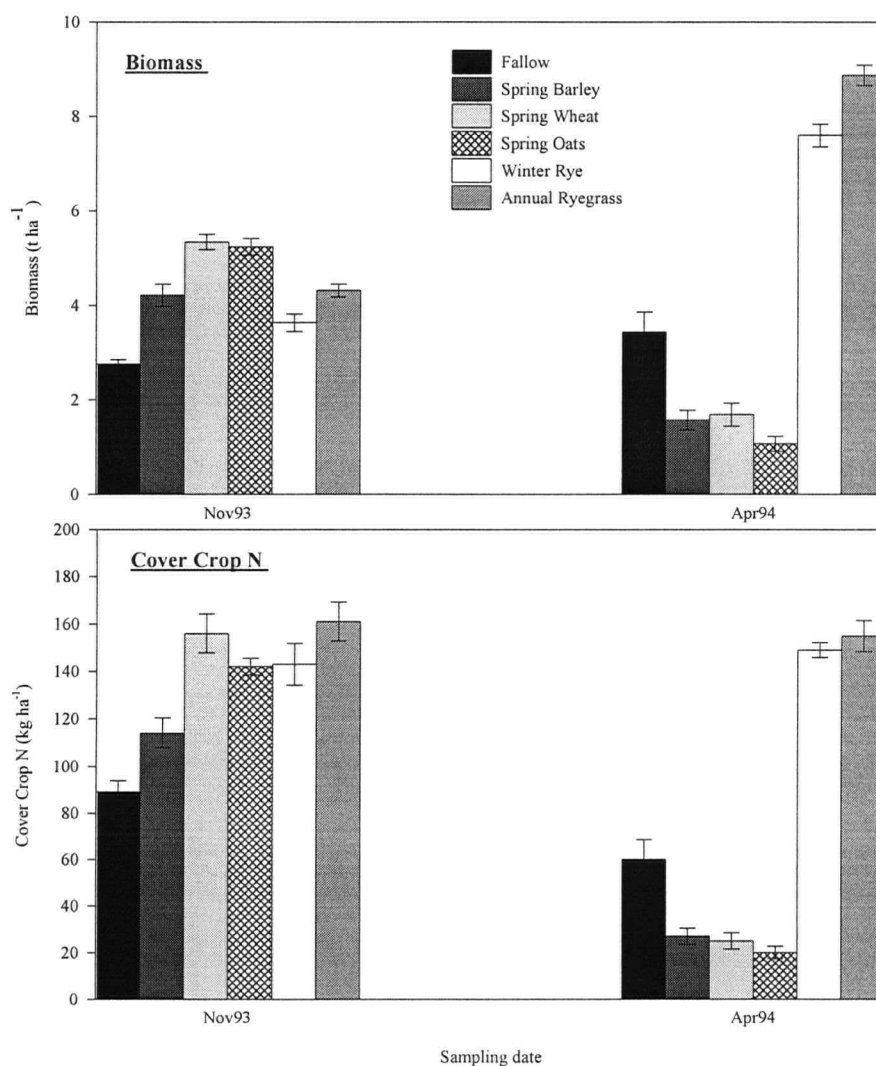
Figure 5-14. Changes in biomass (above) and cover crop N (below) during 1993-94 winter season as influenced by crop species. Error bars represent standard error of the mean (n = 8).

5-1.8. Changes in soil mineral nitrogen during winter

During the 1991-92 winter, the influence of time of sampling and crop species (Table 5-17) indicates that while soil mineral N (0-40 and 0-60 cm layers) in fallow and winter rye plots decreased (by 65 and 40%, respectively), that in autumn-planted spring barley tended to increase (7%) between November 21, 1991 and April 08, 1992 (Figure 5-15). The effect of time of sampling, planting date and nitrogen treatment (Table 5-17) indicates that while there was little change in soil mineral N during winter under the low autumn-N treatment (N-0), greater decrease occurred under high autumn-N treatment (N-100), especially when planting was delayed by one month (Figure 5-15).

During 1992-93 winter, soil mineral N (0-60 cm layer) was influenced by time of sampling, planting date and crop species (Table 5-17). The three-way interaction between time of sampling, planting date and crop species indicates that soil mineral N in the 0-60 cm layer in fallow and September-planted plots decreased during winter but that under August-planted spring barley and winter rye increased (Figure 5-16). The decrease in mineral N under fallow and September-planted cover crops averaged 60 and 69%, respectively. Soil mineral N under August-planted spring barley increased by 48% and 17% under winter rye.

Table 5-17. Repeated measures analysis of variance (P > F values) for planting date (D), autumn soil nitrogen content (N), crop species (C) and time of sampling (T) effects on variations in mineral N in the 0-60 cm soil layer.

Treatment	Soil sampling depth intervals (cm)		
	0-20	0-40	0-60
	.... (P > F values)¶...................		
	1991-92		
T	NS	0.0001	0.0001
T x D	NS	0.0001	0.0001
T x N	0.0054	0.0001	0.0001
T x D x N	NS	0.0144	0.0193
T x C	NS	0.0001	0.0001
T x C x D	0.0130	NS	NS
T x C x N	NS	NS	NS
T x C x D x N	NS	NS	NS
	1992-93		
T	0.0001	0.0001	0.0001
T x D	0.0001	0.0001	0.0001
T x N	0.0001	0.0001	0.0001
T x D x N	NS	NS	NS
T x C	0.0037	0.0001	0.0001
T x C x D	NS	0.0001	0.0001
T x C x N	0.0397	NS	0.0027
T x C x D x N	NS	NS	NS
	1993-94		
T	0.0001	0.0001	0.0001
T x N	0.0001	0.0001	0.0019
T x C	0.0041	0.0001	0.0001
T x C x N	0.0037	NS	NS

¶ Analysis of variance was performed on data transformed to natural logarithm scale; NS, not significant (P > 0.05);
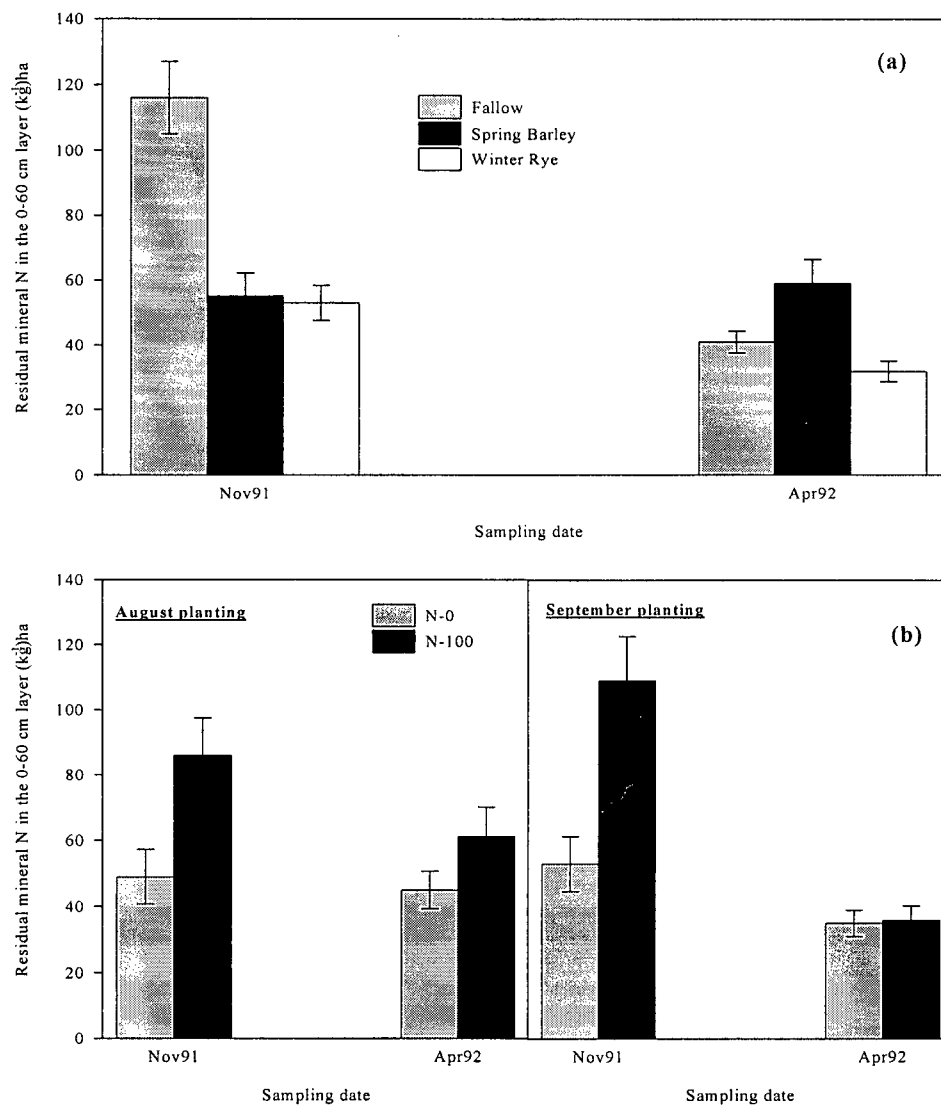
Figure 5-15. Changes in soil mineral N in the 0-60 cm layer during 1991-92 winter as influenced by crop species (a) and by planting date and autumn soil mineral N content (b). Error bars represent standard error of the mean [n = 16 for (a) and n = 12 for (b)].
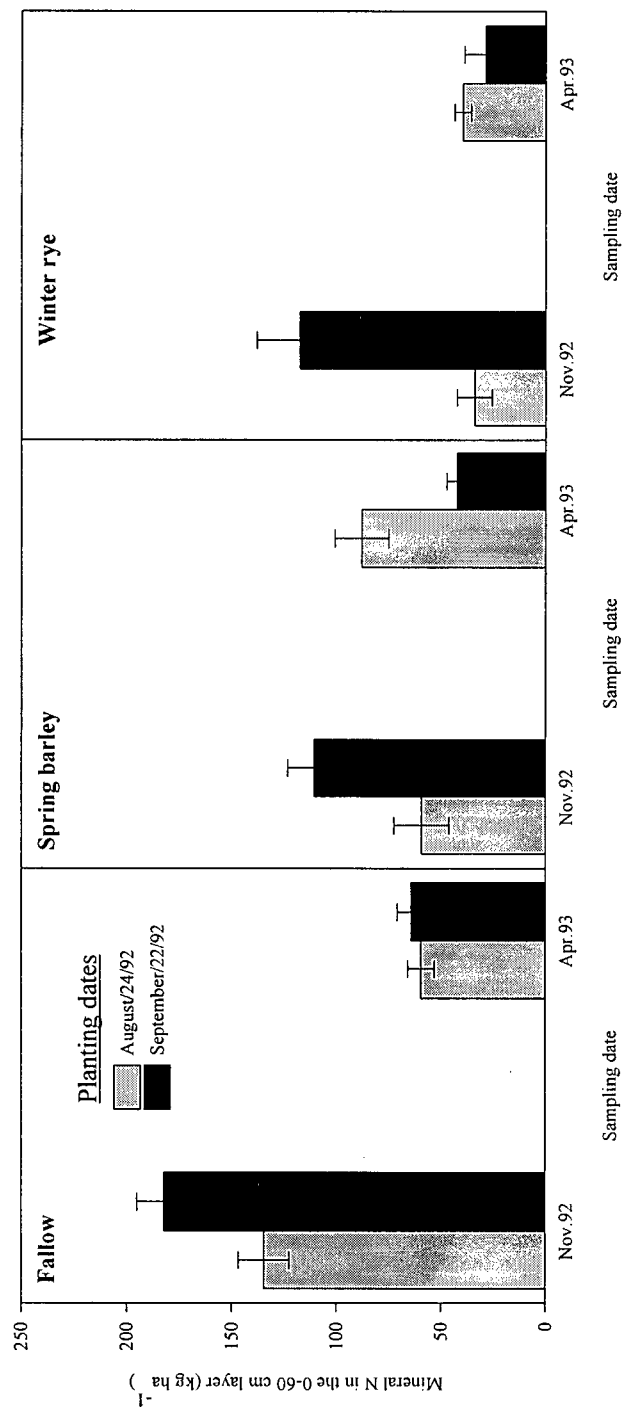
Figure 5-16. Changes in soil mineral N in the 0-60 cm layer during 1992-93 winter season as affected by planting date and crop species. Error bars represent standard error of the mean (n = 8).

In the 1993-94 winter cropping season, soil mineral N in the 0-60 cm layer was influenced by time of sampling, autumn soil mineral N content and crop species (Table 5-17). There was greater decrease in soil mineral N in the N-100 than N-0 treatment (0-60 cm layer) during winter (Figure 5-17). Soil mineral N in the N-100 and N-0 treatments decreased by 51 and 40%, respectively, during winter. The interaction between time of sampling and crop species indicates that during the 1993-94 winter, soil mineral N in the 0-60 cm layer decreased drastically under fallow/chickweed, winter rye and annual ryegrass (72, 51 and 62%, respectively), but a lesser decrease of 22, 27 and 31% occurred under autumn-planted spring barley, spring wheat and spring oat, respectively (Figure 5-17). In fact more soil mineral N was measured under the residues of autumn-planted spring species than either under fallow/chickweed or winter species (rye and ryegrass) in the spring.
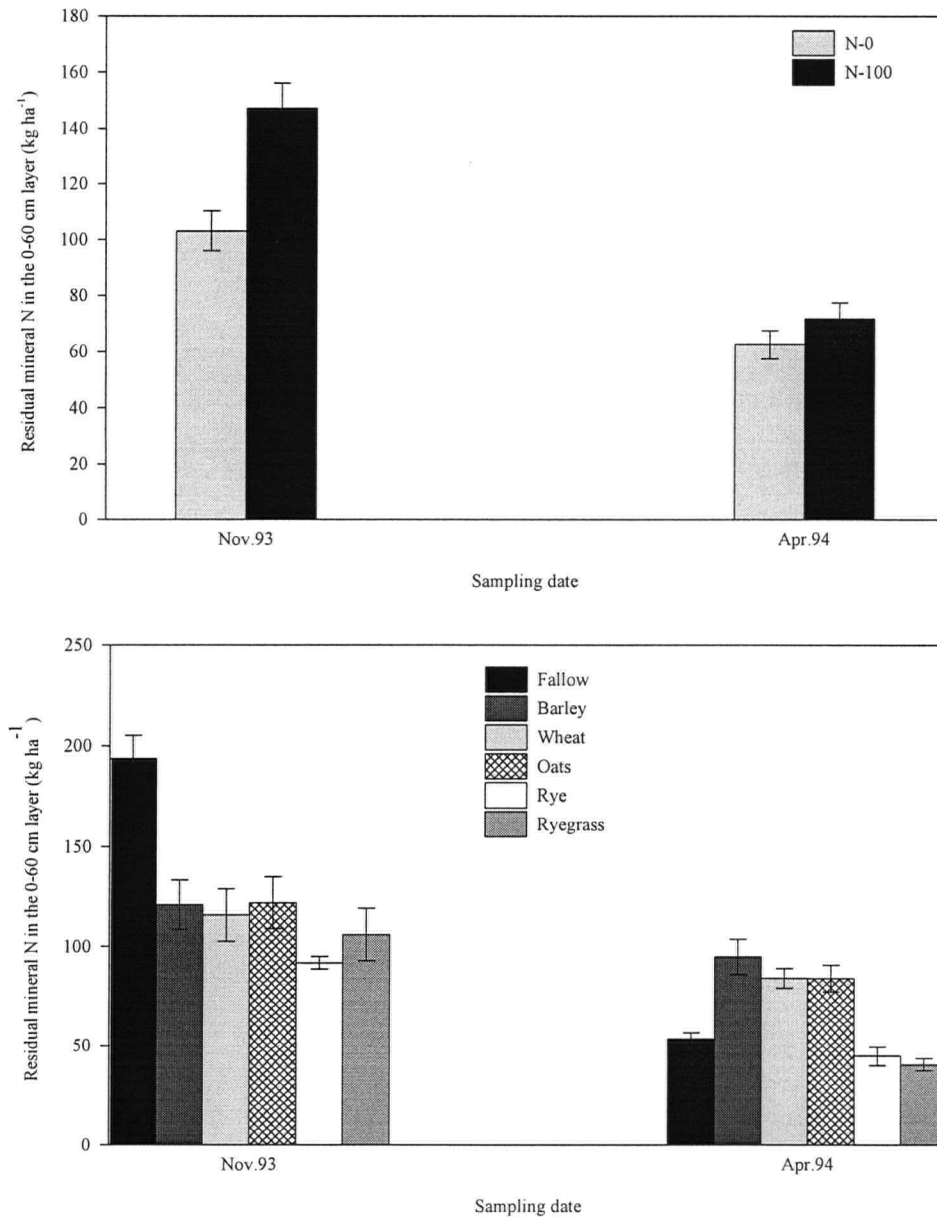
Figure 5-17. Changes in soil mineral N in the 0-60 cm layer over the 1993-94 winter as affected by autumn soil mineral N content (above) and cover crop species (below). Error bars represent standard error of the mean (n = 24 for above and n = 8 for below).

5-1.9. Fertilizer nitrogen balance

At the start of each season (late August), half of the plots received 100 kg N ha^{-1} applied as $Ca(NO_3)_2$. When averaged over planting date and crop species, about 47% of applied fertilizer N was recovered as soil N (ANR_{SOIL}) in the 0-60 cm layer and 28% in the cover crop (ANR_{CROP}) in late November 1991 (Table 5-18), indicating that about 25% of applied fertilizer N was not accounted for. On average, 69% of applied fertilizer N was recovered in fallow soil and most of it was concentrated in the subsurface soil layers. The proportion of fertilizer N recovered under cover crops and distribution in the 0-60 cm layer varied with planting date and crop species. Fertilizer N recovered in August-planted spring barley was 41% and that accounted for in soil was 21%. Most of the fertilizer N under August-planted spring barley was concentrated in the 0-20 cm layer and decreased sharply with depth. In contrast, about 42% of applied fertilizer N was recovered in September-planted spring barley and 54% in soil with uniform distribution in the 0-60 cm layer. On the other hand, the proportions of fertilizer N recovered in August- and September-planted winter rye were 24 and 7%, respectively; apparent N recovery in soil accounted for 36 and 30% for August- and September-planted cover crop, respectively. Generally, apparent recovery of N under winter rye increased sharply with depth, indicating movement of NO_3^- into the subsurface soil layers.

Generally, low fertilizer N recoveries were observed in the crops and soil in the spring of 1992, except under August-planted spring barley which winter-killed in late November 1991. Most of the fertilizer N (82%) in August-planted spring barley was recovered in the soil.

Table 5-18. Balance sheet for applied fertilizer NO_3^--N (100 kg N ha^{-1}) for 1991-92 season as estimated by the difference method.

N recovered in:	August-planted (Aug/19/1991)			September-planted (Sep/16/1991)		
	Fallow	Barley	Rye	Fallow	Barley	Rye
			November 21, 1991			
Cover crop	-	41	24	-	42	7
Soil						
0-20 cm	4	18	4	8	14	4
20-40 cm	20	6	10	30	23	13
40-60 cm	28	-3	22	47	17	13
0-60 cm	52	21	36	85	54	30
Total recovered	52	62	60	85	96	37
Unaccounted for	48	38	40	15	4	63
			April 08, 1992			
Cover crop	-	7	-5	-	3	11
Soil						
0-20 cm	0	7	3	-4	2	0
20-40 cm	2	11	4	-1	-8	1
40-60 cm	9	13	0	3	10	-1
0-60 cm	11	31	7	-2	4	0
Total recovered	11	38	2	-2	7	11
Unaccounted for	89	62	98	102	93	89

Virtually all the fertilizer N was accounted for in the crops and soil before winter leaching period of 1992 (Table 5-19). When averaged over planting date and crop species, apparent fertilizer N recovered in soil was 76% of that applied and 36% was recovered in the cover crop. Comparatively, August-planted spring barley and winter rye recovered a considerably higher proportion of applied fertilizer N before winter leaching period than September-planted cover crops. When averaged over crop species, fertilizer N recovered in August- and September-planted cover crops (ANR$_{CROP}$) were 69 and 4%, respectively. In contrast, the proportions recovered in soil (ANR$_{SOIL}$) for August- and September-planted cover crops were 42 and 86%, respectively. Most of the fertilizer N on fallow plots was measured in the 0-20 cm layer and generally decreased sharply with depth, indicating limited movement into the subsurface layers (20-40 and 40-60 cm). On the other hand, fertilizer N recovered (ANR$_{SOIL}$) under August-planted cover crops gradually decreased and that under September-planted cover crops increased with depth.

Generally, a large proportion of applied fertilizer N was not accounted for in the spring of 1993 on fallow (78%) and September-planted (90%) plots. In contrast, about 50% of applied fertilizer N was recovered in crop and soil (0-60 cm layer) when the cover crops were planted in August. Nearly all the fertilizer N accounted for (89%) was in the soil on August-planted spring barley plots. On the other hand, most of the fertilizer N recovered on August-planted winter rye plots was in the cover crop (80%). The small proportion of applied fertilizer N recovered in winter-killed spring barley residues and the high proportion in soil was attributed to a combination of leaching of N from residues and, decomposition and mineralization of residue N. Lower N recovery in winter rye in spring than in late November 1992 was caused by partial freezing damage to the August-planted crop which received additional 100 kg N ha^{-1} (see Figure

5-7). The small proportion of applied N under fallow and September-planted cover crops was likely caused by NO_3^- leaching during winter.

Table 5-19. Balance sheet for applied fertilizer NO_3^--N (100 kg N ha^{-1}) for 1992-93 season as estimated by the difference method.

N recovered in:	August-planted (Aug/24/1992)			September-planted (Sep/22/1992)		
	Fallow	Barley	Rye	Fallow	Barley	Rye
			November 24,1992			
Cover crop	-	62	75	-	3	5
Soil						
0-20 cm	68	19	20	63	8	19
20-40 cm	18	16	9	26	46	47
40-60 cm	13	14	5	13	27	23
0-60 cm	99	49	34	102	81	89
Total recovered	99	111	109	102	84	94
Unaccounted for	1	-11	-9	-2	16	6
			April 30, 1993			
Cover crop	-	6	36	-	-5	19
Soil						
0-20 cm	3	7	7	-1	4	-1
20-40 cm	6	15	3	2	0	0
40-60 cm	14	27	-1	20	4	0
0-60 cm	23	49	9	21	8	-1
Total recovered	23	55	45	21	3	18
Unaccounted for	77	45	55	79	97	82

In late November 1993, about 50% of applied fertilizer N was accounted for in soil (ANR$_{SOIL}$) and only 8% was recovered in the crop (ANR$_{CROP}$). Most of the fertilizer NO$_3^-$-N was recovered in the 0-20 cm soil layer and decreased sharply with depth (Table 5-20). In all the three seasons, a significant proportion of the fertilizer N was not accounted for in the spring by the difference method.

Table 5-20. Balance sheet for applied fertilizer NO$_3^-$-N (100 kg N ha^{-1}) for 1993-94 season as estimated by the difference method.

N recovered in:	Fallow	Barley	Wheat	Oats	Rye	Ryegrass
			November 24, 1993			
Cover crop	6[¶]	21	13	3	1	3
Soil						
0-20 cm	38	45	30	44	37	46
20-40 cm	11	8	11	6	7	4
40-60 cm	2	1	3	1	2	6
0-60 cm	51	54	44	51	46	56
Total recovered	57	75	57	54	47	59
Unaccounted for	43	25	43	46	53	41
			April 14, 1994			
Cover crop	-3	2	5	1	4	7
Soil						
0-20 cm	1	-1	-3	2	4	-2
20-40 cm	-1	9	12	5	-2	-1
40-60 cm	5	-7	11	17	1	6
0-60 cm	5	1	20	24	3	3
Total recovered	2	3	25	25	7	10
Unaccounted for	98	97	75	75	93	90

¶ Proportion of fertilizer N apparently recovered in chickweed;

5-1.10. Cover crop carbon to nitrogen ratios

In late November 1991, variations in the C/N ratios were largely due to planting date, autumn soil mineral N content and crop species (Table 5-21). The increase in autumn N supply by 100 kg ha^{-1} decreased the C/N ratios substantially in August-planted cover crops but had little influence on the C/N ratios when the cover crops were planted in September (Figure 5-18). Spring barley had higher C/N ratio than winter rye when the two cover crops were planted in August but species differences were not reflected in September-planted cover crops (Figure 5-18). In the spring of 1992, winter rye C/N ratio was significantly higher than that for spring barley residues, despite loss of N from the residues due to leaching and decomposition (Figure 5-19).

Table 5-21. Analysis of variance for the effect of planting date, autumn soil mineral nitrogen content and crop species on C/N ratio during the 1991-92 and 1992-93 cover cropping seasons.

Treatment	Nov/21/1992	Apr/08/1992	Nov/24/1992	Apr/30/1993
	.... (P > F values)			
Planting date (D)	0.0098	NS	0.0087	0.0065
Nitrogen (N)	0.0048	NS	0.0050	NS
D x N	0.0269	NS	0.0385	0.0012
Cover crop (C)	0.0006	0.0001	NS	0.0001
D x C	0.0010	NS	0.0001	0.0001
N x C	NS	NS	0.0064	NS
D x N x C	NS	NS	0.0216	NS
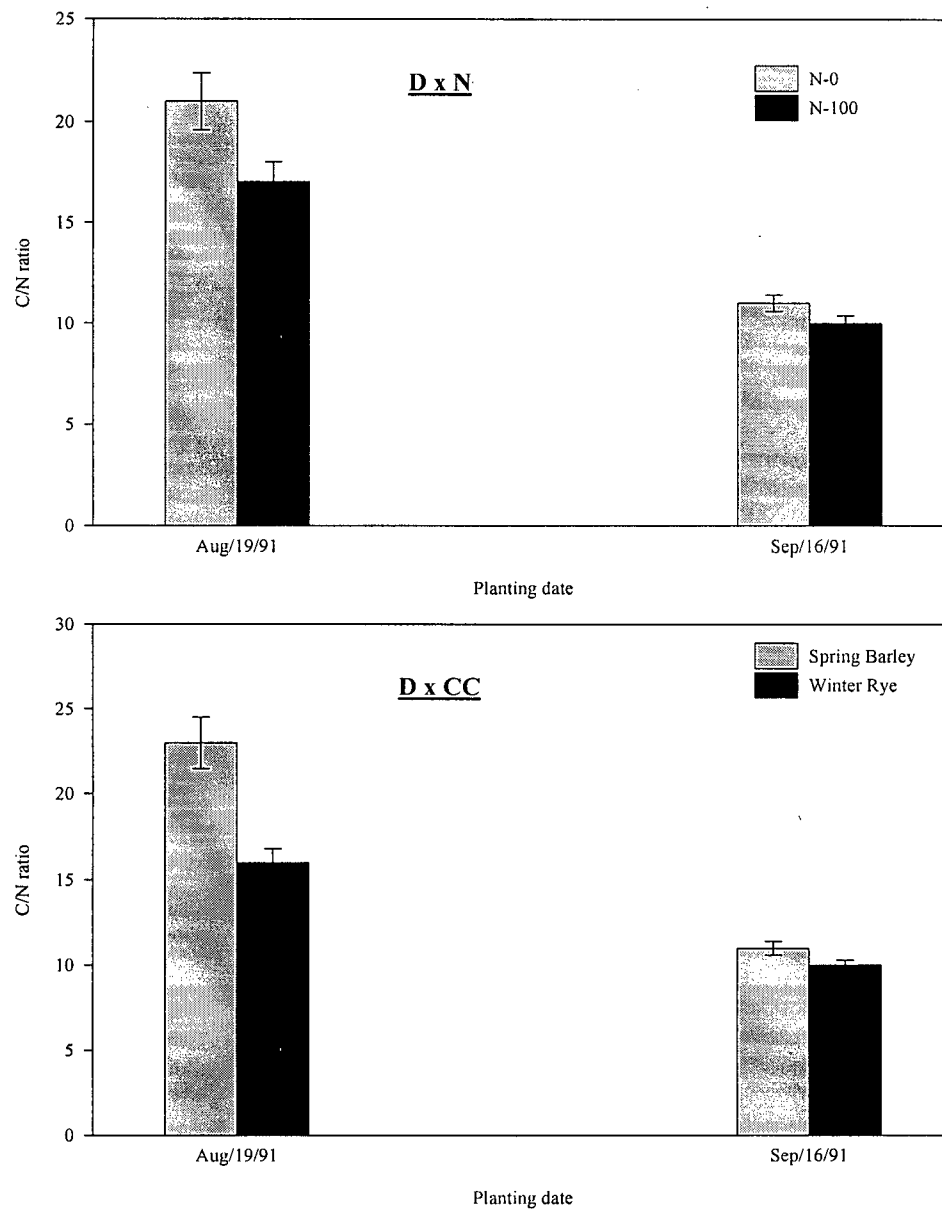
Figure 5-18. Cover crop C/N ratios in late November 1991 as influenced by planting date and autumn soil N content (above) and, planting date and crop species (below). Error bars represent standard error of the mean (n = 8). D x N = planting date x nitrogen interaction; D x CC = planting date x crop species interaction.
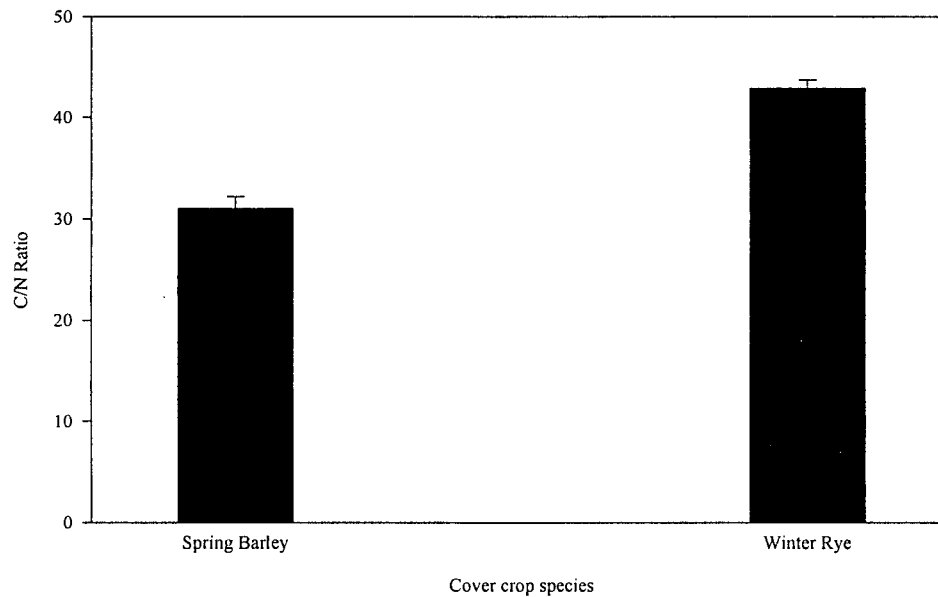
Figure 5-19. The C/N ratios for spring barley residues and winter rye in the spring of 1992. Error bars represent standard error of the mean (n = 16).

Variations in C/N ratios of cover crops in late November 1992 and spring of 1993 were largely due to planting date, autumn soil N content and crop species (Table 5-21). The increase in autumn N supply by 100 kg ha^{-1} decreased the C/N ratios in August-planted spring barley and winter rye by 31 and 9%, respectively, but had no influence on the C/N ratios of the cover crops that were planted in September (Figure 5-20). In the spring of 1993, increase in autumn N supply by 100 kg ha^{-1} caused a 15% decrease in the C/N ratios of August-planted cover crops but slightly increased the C/N ratios by 6% when the cover crops were planted in September (Figure 5-21).
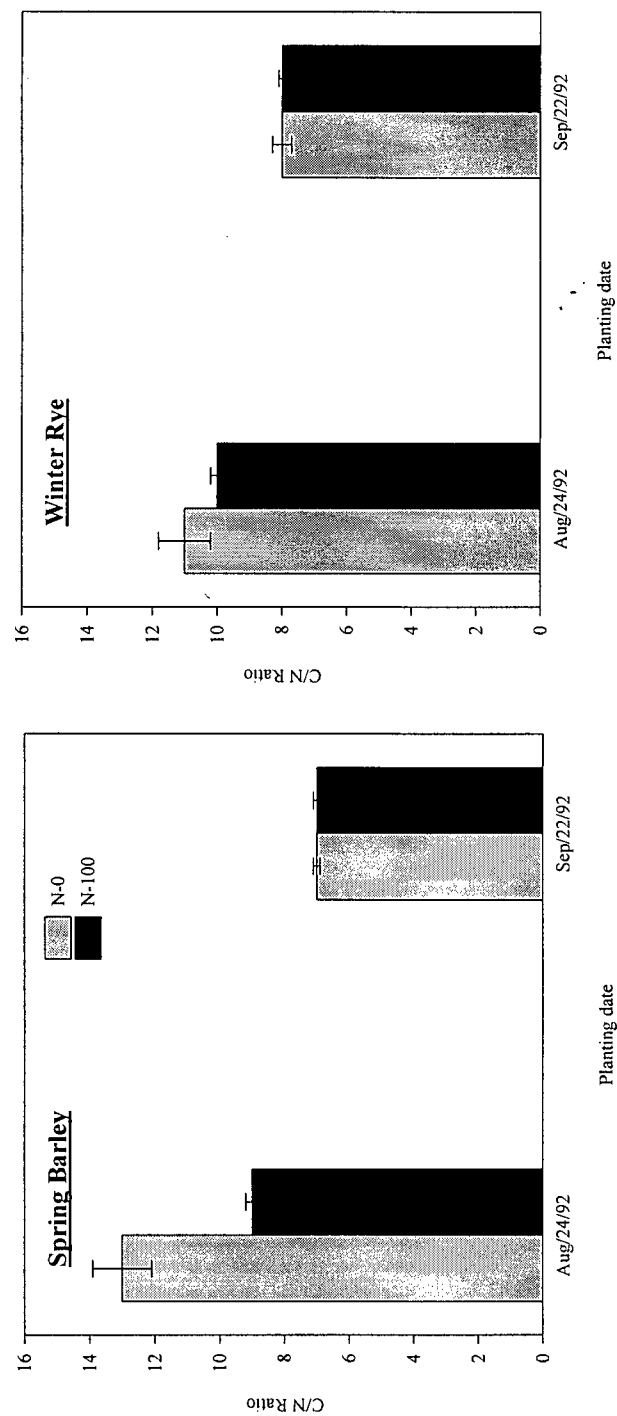
Figure 5-20. Autumn-planted spring barley and winter rye C/N ratios in late November 1992 as influenced by planting date and autumn soil mineral N content. Error bars represent standard error of the mean (n = 4).
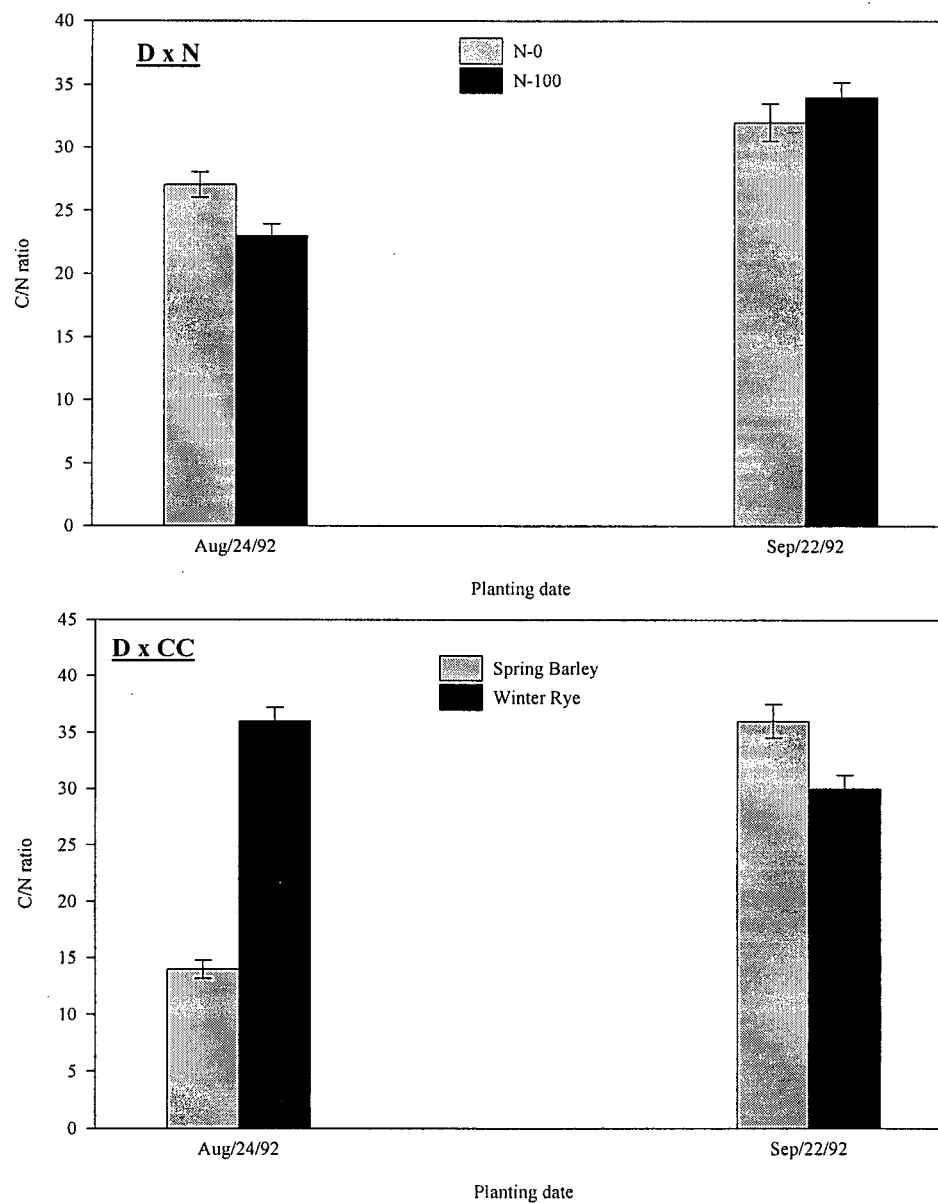
Figure 5-21. Cover crop C/N ratios in the spring of 1993 as influenced by planting date and autumn soil N content (above) and, planting date and crop species (below). Error bars represent standard error of the mean (n = 8). D x N = planting date x nitrogen interaction; D x CC = planting date x crop species interaction

Winter rye had a significantly higher C/N ratio than spring barley residues when the cover crops were planted in August but the opposite was true for September-planted cover crops (Figure 5-21).

In late November 1993 and spring of 1994, variations in the C/N ratios were mainly influenced by crop species (Table 5-22). The C/N ratios of autumn-planted spring species in late November 1993 were generally higher than those of winter species including chickweed in fallow plots but the opposite was true in the spring of 1994 (Figure 5-22).

Table 5-22. Analysis of variance for the effect of autumn soil mineral nitrogen content and crop species on C/N ratio in the 1993-94 cover cropping season.

Treatment	Nov/24/1993	Apr/14/1994
	.... (P > F values)	
Nitrogen (N)	NS	NS
Cover crop (C)	0.0001	0.0077
C x N	0.0090	NS
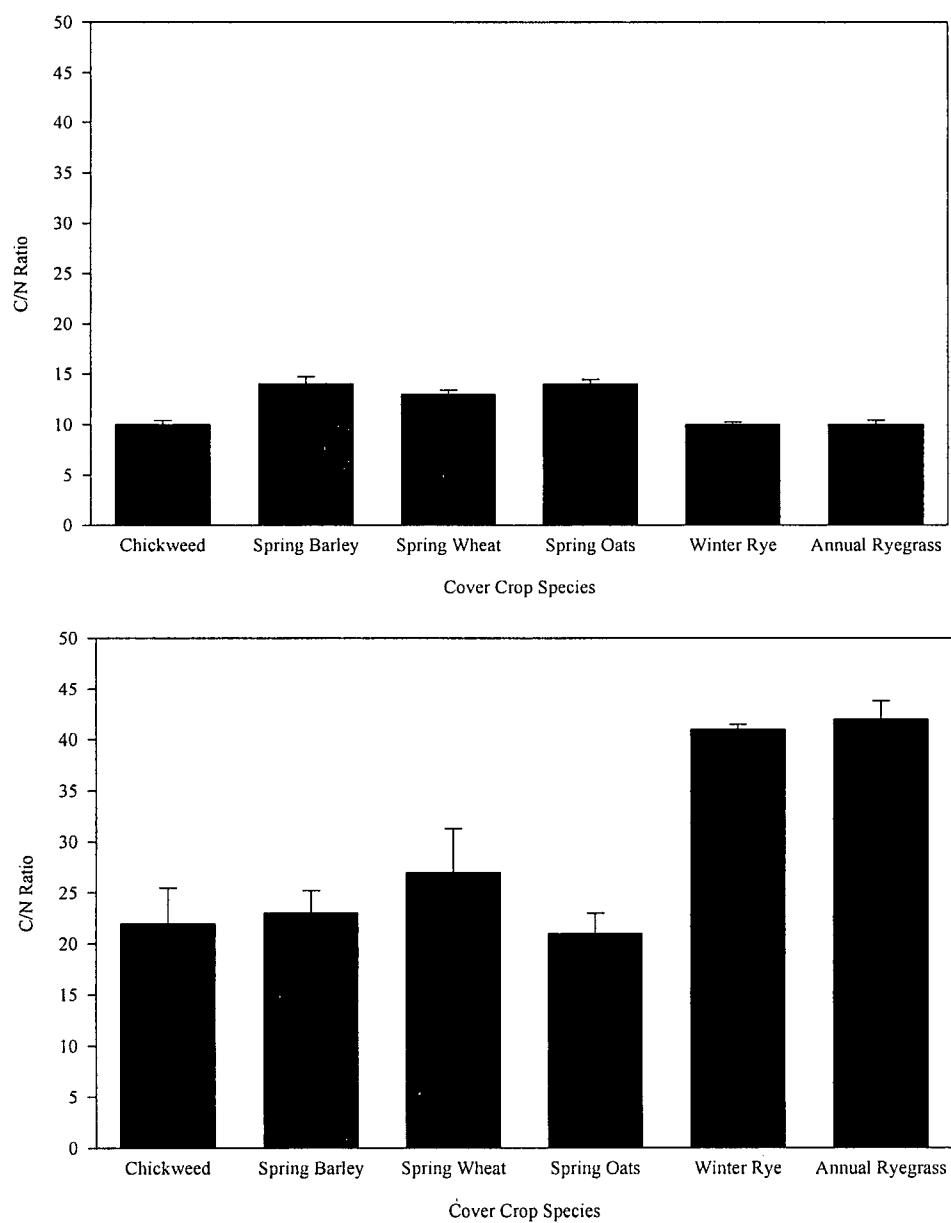
Figure 5-22. Cover crop C/N ratios in late November 1993 (above) and in the spring of 1994 (below). Error bars represent standard error of the mean (n = 8).

5-2. NITROGEN DYNAMICS OF SPRING GRAMINACEOUS COVER CROPS

5-2.1. Nitrogen retention by spring species during winter

The statistical significance of planting date and autumn soil mineral N content effects on spring barley residue biomass remaining (% of DM in November) and N retained (% of TN in November) over the 1991-92 and 1992-93 winter cropping seasons are summarized in Table 5-23. Biomass remaining and N retained in the residues of autumn-planted spring barley at spring time were independent of autumn soil mineral N content but were largely influenced by planting date. In both seasons, planting of spring barley in August increased both the biomass remaining and N retained in the residue over the winter as compared to planting one month later (Figure 5-23). Nitrogen retention values for the 1991-92 winter cropping season were generally lower than those for 1992-93 season.

Table 5-23. Analysis of variance (P > F values) for effects of planting date (D) and autumn soil mineral nitrogen content (N) on residue biomass remaining and nitrogen retention by spring barley over the 1991-92 and 1992-93 winter seasons.

Treatment	Biomass remaining		Nitrogen retained	
	1991-92	1992-93	1991-92	1992-93
Planting date (D)	0.0154	0.0222	0.0066	0.0077
Nitrogen (N)	NS[¶]	NS	NS	NS
D x N	NS	NS	NS	NS

¶ NS, not significant (P > 0.05);
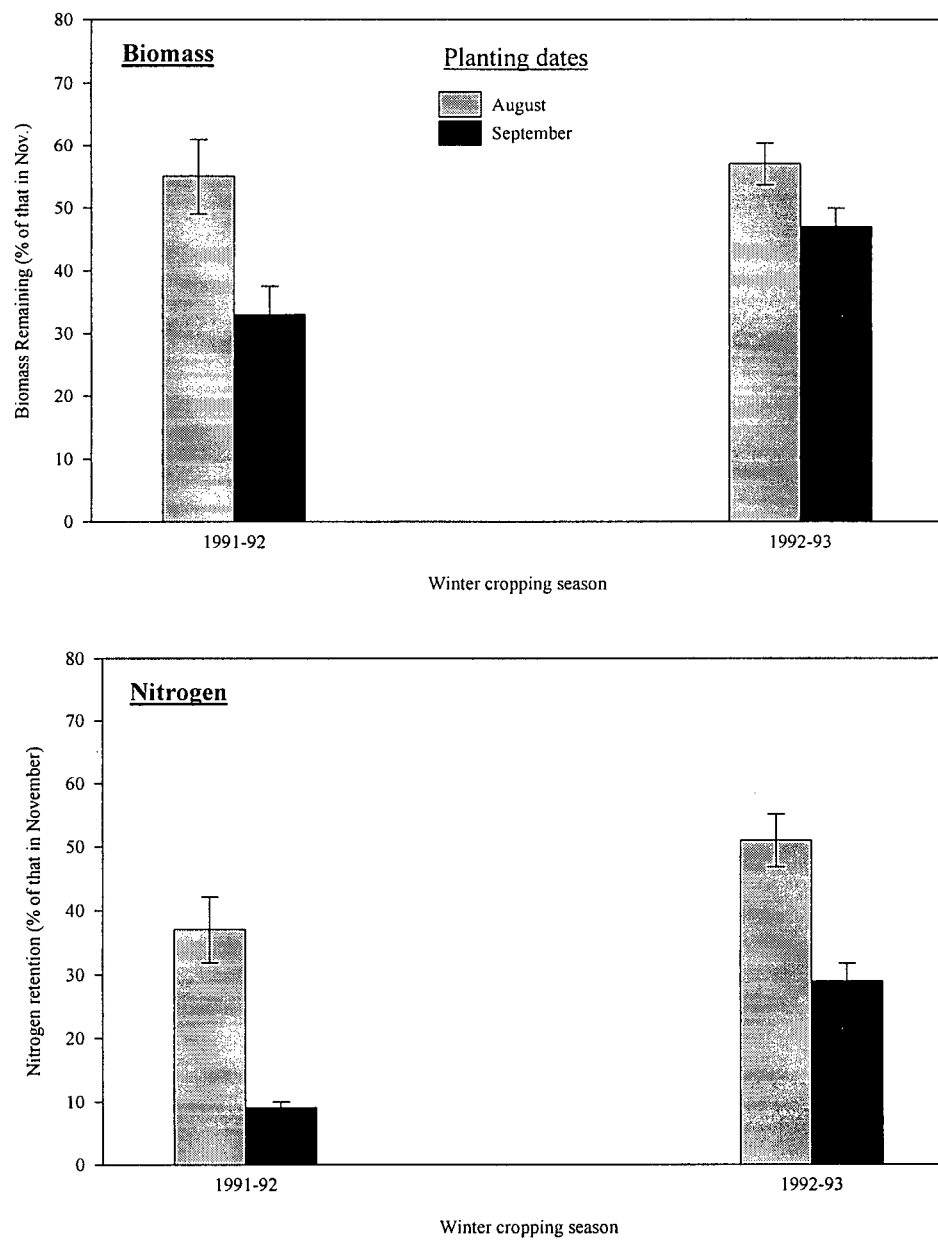
Figure 5-23. Influence of planting date on biomass remaining (above) and N retention (below) by spring barley over the 1991-92 and 1992-93 cover cropping seasons. Error bars represent standard error of the mean (n = 8).

Biomass remaining and N retention over the 1993-94 winter season were independent of autumn soil mineral N content but were influenced by crop species (Table 5-24). The proportions of spring barley residue biomass remaining (%DM in November) and N retained (%TN in November) in residue at spring time were relatively greater than that of spring wheat or oat regardless of whether the residues were in contact with soil (Figure 5-24). Generally, the proportions of biomass remaining and N retained in the residues for the three spring species were higher for samples not in contact with soil than for residues on the soil surface. This was consistent with the 1991-92 and 1992-93 season results for spring barley (see Figure 5-23). In the 1991-92 season, the residue in meshbags was in contact with the soil surface but in the 1992-93 season the residue was placed on a wire mesh table to avoid soil contact and the results indicate that in addition to leaching following rainfall events, microbial decomposition likely contributed to loss of N from meshbag residues that were on the soil surface.

Table 5-24. Analysis of variance (P > F values) for effects of autumn soil mineral nitrogen content (N) and crop species (C) on winter-killed crop residue biomass remaining and nitrogen retention over the 1993-94 winter.

Treatment	Biomass remaining		Nitrogen retained	
	Surface residue	Meshbag residue	Surface residue	Meshbag residue
Nitrogen (N)	NS[¶]	NS	NS	NS
Cover crop (C)	0.0317	0.0023	0.0326	0.0057
N x C	NS	NS	NS	NS

¶ NS, not significant (P > 0.05);
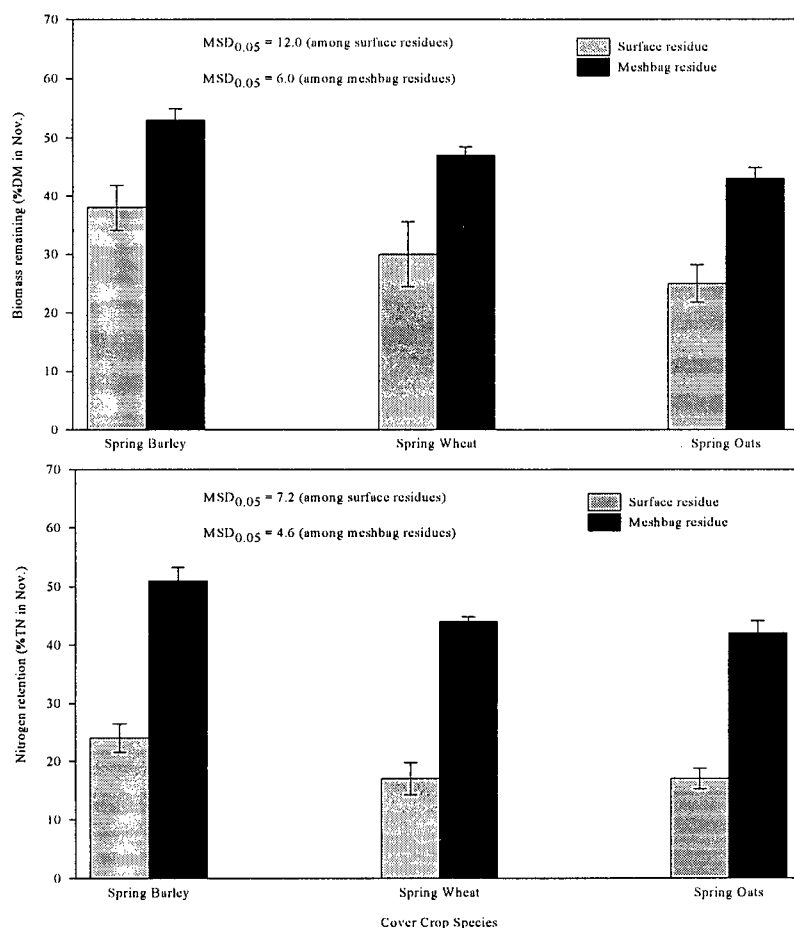
Figure 5-24. Residue biomass remaining (above) and nitrogen retention (below) in the spring of 1994 for surface and meshbag residues not in contact with soil. Error bars represent standard error of the mean (n = 8). $MSD_{0.05}$ is the minimum significant difference according to Tukey's (HSD) test at $P < 0.05$.

5-2.2. Spring species nitrogen fractions at winter-kill

A summary of analyses of variance for the effect of planting date and autumn soil mineral N content on the various spring barley N fractions at winter-kill (late November 1992) is shown in Table 5-25. The proportion of original biomass remaining after cold-water extraction was comparatively greater for August- than September-planted spring barley. Autumn soil mineral N content had no effect on the proportion of biomass remaining after extraction.

Table 5-25. Analysis of variance (P > F-values) for effects of planting date (D) and autumn soil mineral nitrogen content (N) on the various nitrogen fractions of spring barley at winter-kill during the 1992-93 winter cropping season.¶

Treatment	DM	WIN	PN	NPN	NN	AN
Date (D)	0.0099	0.0001	0.0001	0.0261	0.0168	0.0001
Nitrogen (N)	NS	0.0101	0.0144	0.0266	0.0013	0.0001
D x N	NS	0.0131	0.0109	NS	0.0052	0.0001

¶ Analysis of variance was performed on data expressed on a kg ha^{-1} basis, except for DM; NS, not significant (P > 0.05); DM, residue biomass remaining after extraction (% of original); WIN, cold-water insoluble N; PN, TCA-precipitable protein N; NPN, organic nonprotein N; NN, nitrate N; AN, ammonium N;

Cold-water insoluble N (WIN), protein N (PN), NO_3^--N (NN) and NH_4^+-N (AN) for spring barley increased with additional N supply in autumn when the cover crop was planted in August but changed little for the September-planted crop (Figure 5-25). In contrast, organic nonprotein N (NPN) increased when the cover crop was either planted in August relative to September or when autumn soil mineral N content was increased (Table 5-26).
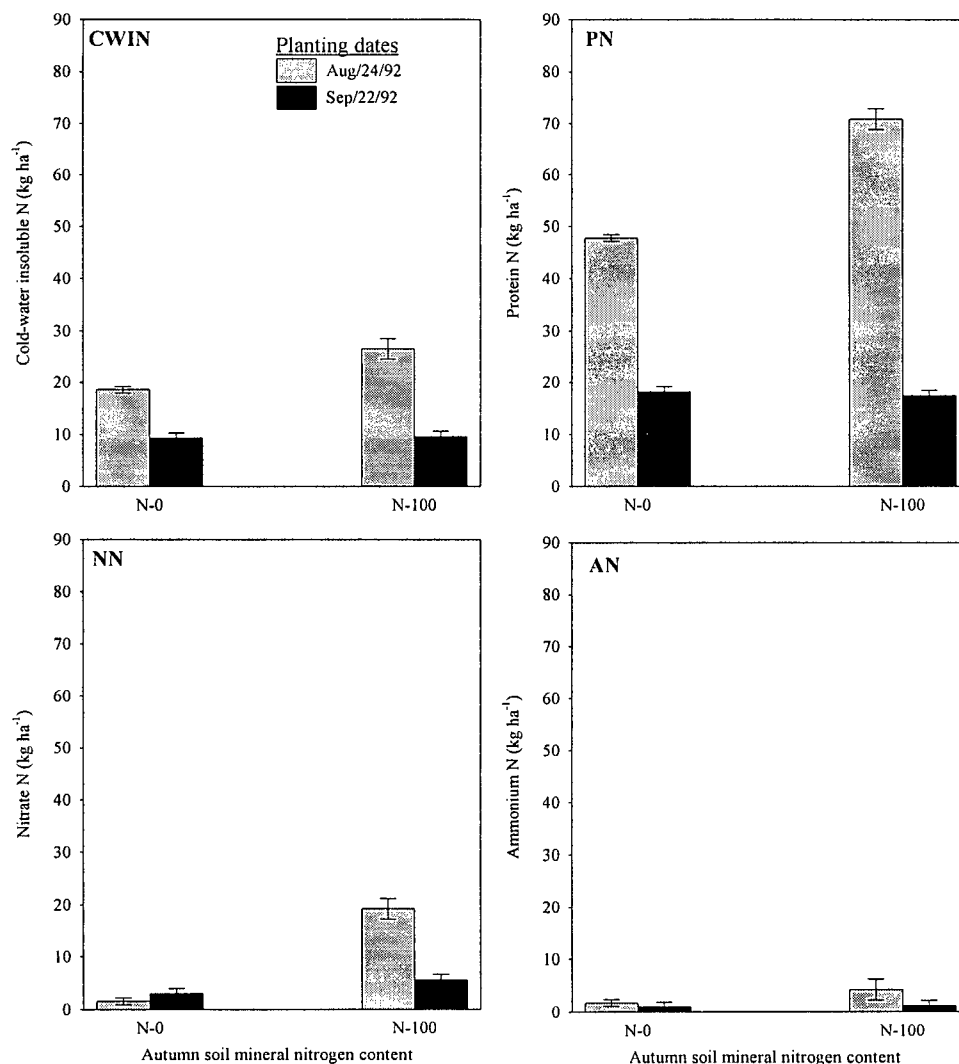
Figure 5-25. Effect of planting date and autumn soil mineral nitrogen content on cold-water insoluble-, protein-, NO₃⁻- and NH₄⁺-N fractions of spring barley at winter-kill in late November 1992. Error bars represent standard error of the mean (n = 4). CWIN, cold-water insoluble N; PN, TCA-precipitable protein N; NPN, organic nonprotein N; NN, nitrate N; AN, ammonium N;

Planting of spring barley in August as compared with September, increased organic NPN by 127% and increasing autumn soil mineral content by 100 kg ha^{-1} caused a 94% increase.

Table 5-26. Effect of planting date and autumn soil mineral nitrogen content on organic nonprotein N (NPN) fraction (kg ha^{-1}) at winter-kill in late November 1992.

Planting date main effect		Nitrogen main effect	
August/24/92	11.8±2.64	N-0	5.8±2.81
September/22/92	5.2±0.44	N-100	11.2±0.54

The effects of autumn soil mineral N content and crop species on the various spring species N fractions at winter-kill (late November 1993) are shown in Table 5-27. Biomass remaining (% of biomass before extraction) after cold-water extraction was not influenced by autumn soil mineral N content but was significantly affected by crop species. Spring barley and wheat residue biomass remaining after extraction were comparable but significantly greater than that of spring oat (Table 5-28).

At winter-kill in late November 1993, none of the N fractions were influenced by autumn soil mineral N content but were largely dependent on crop species (Tables 5-27). Spring barley and oat contained similar amounts of cold-water insoluble N but significantly less than that of spring wheat (Table 5-28). Spring wheat and oat had the same amount of N associated with soluble proteins but considerably greater than the amount in spring barley. The three species had comparable amounts of organic nonprotein N (NPN), NO_3^--N and NH_4^+-N.

Table 5-27. Analysis of variance (P > F-values) for effects of autumn soil mineral N content (N) and cover crop species (C) on the various spring species nitrogen fractions at winter-kill in late November 1993.¶

Treatment	DM	WIN	PN	NPN	NN	AN
Nitrogen (N)	NS	NS	NS	NS	NS	NS
Cover crop (C)	0.0001	0.0001	0.0012	NS	NS	NS
N x C	NS	NS	NS	NS	NS	NS

¶ Analysis of variance was performed on data expressed on a kg ha^{-1} basis, except for DM; DM, residue biomass remaining after extraction (% of original);WIN, cold-water insoluble N; PN, TCA-precipitable protein N; NPN, organic nonprotein N; NN, nitrate N; AN, ammonium N; NS, not significant (P > 0.05);

Table 5-28. Effect of cover crop species (C) on the various spring species nitrogen fractions at winter-kill in late November 1993.¶

Cover crop	DM	WIN	PN	NPN	NN	AN
	.... (kg ha^{-1})					
Spring barley	70a	30b	37b	25a	19a	3a
Spring wheat	68a	47a	57a	31a	18a	3a
Spring oat	60b	30b	58a	29a	22a	3a

¶ DM, residue biomass remaining after extraction (%of original DM); WIN, cold-water insoluble N; PN, TCA-precipitable protein N; NPN, organic nonprotein N; NN, nitrate N; AN, ammonium N; values in columns followed by the same letter(s) are not significantly different according to Tukey's (HSD) test (P > 0.05);

5-2.3. Protein nitrogen fractions and nitrogen retained in meshbag residues in the field

Generally, most of the N accumulated by the cover crops was in the form of organic N. In 1992-93 and 1993-94, spring species in meshbags were placed on wire mesh tables to estimate N retention without contamination from soil. The proportion of N retained (NR) in the residues of autumn-planted spring species during winter was compared with cold-water insoluble N (WIN) and with total protein N (WIN + PN) as paired observations using a two-tailed T test (Table 5-29).

Table 5-29. Comparison of cold-water insoluble N (WIN) and total protein N fractions with N retained in meshbag residues in the field in 1992-93 and 1993-94 seasons.¶

	Autumn planting dates		
Nitrogen fractions	August/24/1992	September/22/1992	August/24/1993
	.... (%TN)		
WIN	22(±1.2)	25(±1.7)	26(±1.9)
WIN + PN	79(±1.4)	72(±1.8)	62(±2.0)
NR	48(±1.2)	28(±1.8)	48(±2.1)
Comparisons	.... (P > T)		
WIN vs NR	0.0001	0.2904	0.0007
(WIN + PN) vs NR	0.0001	0.0001	0.0001

¶ WIN and PN, cold-water insoluble- and soluble protein N fractions, respectively (% of total N for all fractions); NR, N retained in meshbags placed on mesh tables to avoid soil contact (% of total N in November 1992 or 1993); values in brackets are standard errors of the means (n = 8 for 1992-93 and n = 24 for 1993-94);

The proportion of N retained (NR) in the residues following winter-kill was greater than that of cold-water insoluble N (WIN) but less than that of total protein N (WIN + PN) when the cover crops were planted in August. When cover crops were planted in September, the proportion of N retained in the residue was similar to that of cold-water insoluble N but significantly less than that of total protein N. It appears that for August-planted spring barley, in addition to structural N (cold-water insoluble N), a proportion of the N associated with cold-water soluble protein N was retained in the residue following winter-kill. In contrast, when spring barley was planted in September, only the N associated with cold-water insoluble fraction (WIN) was retained in the residues.

Chapter 6: DISCUSSION

6-1. Cover crop and soil nitrogen before winter leaching period

August- relative to September-planting of spring barley and winter rye increased N uptake before winter leaching period of 1991 and 1992. Although increased N uptake was accompanied by reduction in residual mineral N (0-60 cm layer), this was only significant in late November 1992. This suggested that, apart from changes in soil mineral N due to N uptake by cover crops in 1991, other processes, most likely NO_3^--N leaching from the 0-60 cm soil layer, denitrification and immobilization contributed to variations in residual mineral N. Displacement of NO_3^- from the surface 20 cm to the subsurface soil layers in 1991 started in the last week of August due to intense rainfall events (see Figure 4-2) and was evident at the late planting date (see Table 5-1). This early displacement of NO_3^- may have resulted in movement of some of the NO_3^- below the 0-60 cm soil layer when intense rainfall resumed in November. The differences in soil mineral N due to N uptake were likely offset by losses due to a combination of leaching of NO_3^-, denitrification and immobilization. The water table rose to within 20 and 60 cm of the soil surface in late November 1991 and 1992, respectively. This may also have influenced soil N measurements in 1991 through a dilution effect.

Widdowson et al. (1987) in Great Britain, and Sorensen (1992) in Denmark have reported an inverse relationship between N uptake and residual mineral N with winter wheat and annual ryegrass, when the cover crops were planted early. Winter wheat was planted in September and October, while annual ryegrass was planted in the middle of July, beginning of August and middle of August. Increased growth period, warmer soil temperatures and longer daylength associated with early planting of winter crops stimulates tillering. Development of greater numbers of tillers per unit area and higher total biomass production increases the potential for

more cover crop N accumulation. Thus, N uptake by cover crops is related to the length of time the crop is allowed to grow. When cover crops are primarily planted to capture NO_3^-, extending the vegetative growth period will maximize N uptake. But the N taken up by cover crops during autumn and early winter months is the most critical in terms of reducing NO_3^- leaching into groundwater (Bergstrom and Brink, 1986).

Spring barley was not different from winter rye in terms of biomass production and N uptake. The difference in growth stages of spring barley and winter rye (especially for August-planted crops) at the time of sampling in late November is large (see Table 3-5.), but winter rye produces more tillers compared to spring barley. Despite winter rye and spring barley absorbing similar amounts of mineral N by late November 1991 and 1992, less mineral N was measured in winter rye than spring barley plots in the 0-60 cm soil layer. In fact planting of winter rye in August in 1992 caused greater reduction in soil mineral N (0-60 cm layer) than spring barley but the two cover crops had little influence when planted a month later (see Figure 5-3). The data also indicated that under low autumn N supply, winter rye resulted in greater soil mineral N reduction than spring barley but the two cover crops were comparable when an additional 100 kg N ha^{-1} was applied. This was likely due to species differences in the root system of winter rye and spring barley; for example, differences in root biomass and consequently amount of N accumulated in roots. Mitchell and Teel (1977) in their evaluation of winter annual cover crops for no-tillage corn production have reported a 4-fold increase in root biomass and N accumulated in roots of winter rye relative to that of spring oat. These parameters were not determined in this study. Also, the rhizosphere plays a major role in terms of plant nutrient turnover and availability; among other factors the type and quantity of root exudates that influence rhizosphere microbial activity depend on plant species (Rovira and Davey, 1974). The difference thus may suggest greater immobilization of mineral N in the root zone (Jansson and Persson, 1982) of

winter rye than spring barley. Also, root exudates stimulate microbial growth and activity in the rhizosphere of plants (Rovira, 1965). Woldendorp (1963) has suggested that roots and root exudates of plants may contribute sufficient organic matter to stimulate denitrification. The difference in type and quantity of root exudates of spring barley and winter rye may have resulted in different denitrification losses under the two cover crops.

6-2. Impact of cover cropping on soil NO_3^- before winter leaching period

Cover crops minimize the problem of NO_3^- leaching by assimilation of mineral N, thus converting the most readily leachable NO_3^- to organic forms. Thus, planting of cover crops can decrease NO_3^- leaching by reducing the amount of the available form of N for leaching during winter. I made assessment of cover cropping effect on soil NO_3^--N by calculating percent NO_3^--N reduction (PR) due to the cover crop. This method has been used by Meisinger et al. (1991) and Brandi-Dohrn et al. (1997) to estimate the impact of cover crops on soil NO_3^--N. However, one weakness of the method may arise on particular soils, especially on fine-textured or sloping soils where cover cropping can reduce runoff and increase water infiltration in cover crop relative to fallow plots (Langdale et al., 1979; McVay et al., 1989; Hermawan, 1995); and thus overestimate cover crop influence on soil NO_3^--N content. In this study, the decrease of NO_3^--N in the 0-60 cm layer due to cover cropping (PR) was variable among the years, and generally ranged from 33 to 91%.

The values reported in this study represent potential reduction in NO_3^--N leaching as actual leaching measurements were not obtained. Similar field plot studies in other regions have shown variable results. Staver and Brinsfield (1990) in a 1-year study have reported a 77% reduction in NO_3^--N (0-30 cm layer) due to winter rye (planted in first week October) cropping on silty loam soil in Maryland. In Denmark, Nielsen and Jensen (1985) in a 2-year study using annual ryegrass

on a sandy loam soil found that the cover crop reduced NO_3^--N by 62% in the 0-100 cm layer. In France, a 1-year field plot study with rape, radish and winter rye (planted in October) found reduction in NO_3^--N due to cover cropping of 35, 44 and 59%, respectively, in the 0-100 cm layer (Muller et al., 1989). Brandi-Dohrn et al. (1997) in a 3-year study have reported percent NO_3^--N reduction due to cover cropping with winter rye ranging from 25 to 62% on Willamette loam in Oregon. A 1-year ^{15}N lysimeter study in France found that annual ryegrass cover crop reduced NO_3^--N leaching by 64% (Martinez and Guiraud, 1990). While all the studies reviewed indicate that cover cropping reduces NO_3^--N and thus the potential to leach out of the root zone, it is difficult to compare the results due to inadequate reporting of such factors as soil mineral levels at planting, winter soil and air temperatures, winter precipitation, cover crop biomass production, cover crop N uptake and NO_3^--N leaching losses. Further, as indicated above, estimates of the impact of cover crops on NO_3^--N in the studies were based on different depth intervals.

When planted in August, winter rye was more efficient than spring barley in reducing soil NO_3^- levels in the 0-60 cm layer before winter leaching period of 1992 but when planted one month later the two cover crops were equally less effective (see Figure 5-5). This was consistent with soil mineral N data (see Figure 5-3) and was attributed to species differences in the root systems of the cover crops, for example root biomass and N content. Measurements of the N accumulated in cover crop roots are usually difficult to make but are equally as important as those for N in the aboveground portions. Despite differences due to growth stages and soil N contents at sampling time, literature estimates of root N for winter rye and annual ryegrass are 25 and 33% of total N (root N + shoot N), respectively (Pieters, 1927; McVickar et al., 1946; Mitchell and Teel, 1977). Root biomass and total N were not determined in this study. The inclusion of root contribution to total cover crop biomass and N measurements may likely

improve the relationship between biomass production and residual mineral N in late autumn as soil N mineralization may be negligible due to cold temperatures.

6-3. Cover crop and soil nitrogen after winter leaching period

In all the three winter cropping seasons, spring species that were planted in August winter-killed in late November (start of winter). Their biomass and N decreased considerably during winter and the decrease was accompanied by a significant increase in soil mineral N in the 0-60 cm layer relative to the amount measured in fallow plots in spring (see Figures 5-10 and 5-11). This observation is the first to be reported on Lower Fraser Valley soils and indicates that August planting of spring species may be beneficial in terms of conserving autumn mineral N (NO_3^- in particular).

August planting of spring species results in greater biomass production and N uptake before winter leaching period (Bomke and Temple, 1994). There are also indications that August-planted spring species have a greater potential to retain accumulated N than September-planted cover crops by spring time (see Figure 5-23). In addition to cold-water insoluble N (structural N), August-planted spring species may retain some of the water-soluble N, most likely N associated with soluble proteins (see Table 5-29). This may be explained as follows; plants contain very diverse secondary products (phenolic compounds) and these products, especially tannins and lignins accumulate with plant age (Albersheim, 1965; Swain, 1965; Mengel and Kirkby, 1987; Marschner, 1995; Sorenson, 1992; Walton, 1983). Low molecular weight phenolic compounds combine with proteins reversibly by hydrogen bonding, and irreversibly by oxidation to quinones followed by covalent condensations (Loomis and Battaile, 1966; Loomis, 1974). Higher molecular weight phenolics (tannins) form insoluble complexes with proteins, removing them

from solution (Swain, 1965; Loomis, 1974; Gagenheimer, 1990). The interaction of plant phenolics with proteins at the time of winter-kill thus may not only limit the chances of enzymatic protein breakdown but also alter their physical properties and confine protein N within the residues. Accumulation of fibre content (lignin in particular) with plant age also increases the mechanical strength of the residues and may not only reduce microbial accessibility but also cause resistance of the residues to raindrop impact.

The effect of August-planted spring species mulch on soil mineral N may indicate that residue N readily mineralizes in the spring thus increasing soil mineral N content and may be particularly significant with respect to main season crop production as N uptake and N availability may be synchronized. This can influence the amount of supplemental N fertilizer required for subsequent summer crop production. In the Netherlands, it has been determined that optimum fertilizer N application rate decreases with increasing amounts of soil mineral N (Neeteson et al., 1989).

The processes of organic matter decomposition are largely controlled by soil microorganisms and are therefore influenced by weather (temperature and moisture), pH and soil aeration (Jenkinson, 1981). Another factor that influences the breakdown of organic matter is the chemical make-up. Generally, crop residues contain about the same amount of carbon (approx. 40% on dry-weight basis) and their N contents are usually compared on the basis of C/N ratios. In this study carbon content (%DM) of cover crops ranged from 37 to 44%. Although not always, the C/N ratio can be useful in predicting residue decomposition rates. A negative correlation exists between decomposition rate constants and the C/N ratio of plant residues (Tian et al., 1992; Christensen, 1986; Keya, 1975; Nyamai, 1992). Plant materials that are low in lignin and other polyphenols, and high in N and soluble carbohydrates, generally undergo relatively rapid

decomposition (Tian et al., 1995). Thus the rate of initial breakdown is dependent on the age of the tissues as well as species.

Three possible factors may be responsible for rapid release of N (see Figures 5-10 and 5-11) from the residues of August-planted spring species in spring. Firstly, the residues provide a favourable habitat for soil fauna, notably earthworms (*Lumbricus rubellus*) which may accelerate decomposition. Hermawan (1995), while working on the same plots (1993-94 season) reported a higher earthworm population in the spring on spring barley residue than on bare (fallow) plots. Secondly, mineralization of N from plant residues is dependent on the quality of the residue in terms of lignin and polyphenol contents, and C/N ratio. An inverse relationship exists between the rate of plant residue decomposition and the three residue quality factors (Tian et al., 1992). Parnas (1975) studied the relationship between N immobilization and C/N ratio, and concluded that N immobilization occurs if the residue has a C/N ratio greater than 30 because all the N is utilized by microorganisms. Biochemical composition (lignin and polyphenols) of the cover crops were not determined in this study but the quality of August-planted spring species at winter-kill in terms of the C/N ratio was in the range that favours net N mineralization (see Sec. 5-1.10). The C/N ratios for August-planted spring species in all the three seasons ranged from 13 to 25 under low autumn soil N (N-0) and 9 to 20 under high autumn soil N (N-100). It is also possible that, readily available C from cover crop mulch can have a priming effect on soil organic matter, enhancing mineralization of soil organic N (Stevenson, 1982).

August-planted winter rye was susceptible to freezing damage in late November, especially when autumn soil N content was increased by 100 kg ha^{-1} (see Figure 5-7). Several factors are known to influence hardening of plants. Susceptibility of August-planted winter rye to freezing damage may be explained as follows. August planting exposes winter rye to long days and high temperatures, both of which enhance growth rate and developmental stages of the plants.

Freezing tolerance in winter annuals is inversely related to both growth rate and developmental stages of plants (Levitt, 1980). Many reports (Levitt, 1956) indicate that full hardening of plants is not achieved in the presence of excess N. This is attributable to the fact that N also promotes growth rate through increase in leaf area index and therefore the potential for photosynthesis; consequently root growth and biomass production increase (Marschner, 1995: Wild, 1988). Nitrogen also increases the size of plant cells and reduces the thickness of their walls and thus makes plants more susceptible to freezing damage (Wild, 1988).

Despite the fact that August-planted winter rye may be as effective as spring species in accumulating and retaining significant amounts of N during winter, other studies indicate that high C/N ratios due to rapid spring growth result in N immobilization, increasing fertilizer needs for summer crops (Hargrove and Frye, 1987; Wagger and Mengel, 1988; Holderbaum et al., 1990). The potential for winter rye to release N during summer in these studies was indirectly determined using response of summer crops (biomass and N uptake) as an estimator of N contribution by the cover crop either after incorporation or herbicide-kill in the spring. In this study, C/N ratios for winter rye in the spring varied among the years and ranged from 31 to 44 (see sec. 5-1.10).

6-4. Fertilizer nitrogen balance

Before winter leaching period of 1993-94, about 42% of the fertilizer N was not accounted for in soil and crop (see Table 5-20) despite little indication of leaching. Total precipitation between August and November 1993 was only 40% of the long-term (1937-90) normal, while that between August and November in 1991 and 1992 was 103 and 90% of the long-term normal, respectively (see Table 3-1). Lack of complete fertilizer N recovery may be explained in three

ways. Firstly, N was not limiting at the study location (see Table 5-1) and it is evident from statistical analysis (see Table 5-4) that cover crop biomass and N uptake were not influenced by the addition of 100 kg N ha^{-1}; thus the difference method may have resulted in small apparent fertilizer N recovery by the cover crops. Secondly, there is evidence that although cropping (especially with grasses) reduces soil mineral N content through uptake, rhizosphere microorganisms can utilize root exudates as a source of energy to cause immobilization of soil mineral N (Goring and Clark, 1948; Jansson and Persson. 1982). Thirdly, decomposing potatoes (*Solanum tuberosum* L.) from the previous crop at the 1993 location (L93) may have supplied a readily available source of energy for microorganisms to cause immobilization of fertilizer NO_3^-.

The difference method relies on the assumption that contribution of soil N to crop uptake is the same for the fertilized and unfertilized treatments. But many studies have shown that application of fertilizer N enhances uptake in the fertilized crop. This phenomenon has been explained in two ways. Firstly, fertilizer N application stimulates root development and enhances N uptake due to rhizosphere effects (Kissel and Smith, 1978; Fried and Broeshart, 1974; Aleksic et. al., 1968). Secondly, fertilizer N stimulates the mineralization of soil N, which leads to increased N consumption by the fertilized crop (Westerman and Kurtz, 1974; Chichester and Smith, 1978; Filimonov and Rudelev, 1977; Kissel and Smith, 1978). In order to achieve meaningful results, there must be crop response to N application which sets the precondition that soil N must be at suboptimal levels.

Many experiments with ^{15}N have shown that plant uptake efficiency of fertilizer N does not often exceed 50 to 60% of that applied (Herron et al., 1968; Hauck, 1971; Westerman, 1972; Powlson et al., 1986; Ditsch et al., 1993), and under certain conditions may be much less. The remaining N is not necessarily subject to loss or leaching, as some will be incorporated into soil organic matter by microbial means. For example, Smith and Power (1985) reported that 20 to

50% of the fertilizer N not initially utilized by perennial grass in the semiarid northern Great Plains is incorporated into soil organic matter. When leaching and denitrification losses are negligible during the main season, winter cover crop biomass and N uptake increase with increasing rates of fertilizer N application to the main season crop (Ditsch, et al., 1993; Shipley et al., 1992).

Low apparent fertilizer N recovery in the cover crop and soil in the spring of all the three seasons was evident. The low apparent N recovery in spring species residues was attributed to a combination of surface decomposition of the residues and leaching of organic N compounds from the residues due to winter rainfall events. The low apparent N recovery in the living cover crops (winter species) was mainly due to the fact that there was generally little additional N uptake in the spring and that the August-planted cover crop which received 100 kg N ha^{-1} was susceptible to freezing damage in late November (see Figure 5-7). This resulted in a net loss of N during winter in August-planted winter rye in the first two seasons (1991-92 and 1992-93). Generally, low apparent fertilizer NO$_3^-$ recoveries in soil may have been caused by NO$_3^-$ leaching during winter (Kowalenko, 1987b and 1989), denitrification and incorporation of fertilizer NO$_3^-$ into soil organic matter (Smith and Power, 1985). Although the three processes may account for NO$_3^-$ loss during winter, a significant proportion of the loss is most likely due to leaching. Bomke et al. (1994) reported the consistent appearance in spring of N deficiency symptoms on unfertilized winter wheat in south coastal B.C. and attributed it NO$_3^-$ leaching during winter. Paul and Zebarth (1997) partitioned N losses to denitrification and leaching from autumn-applied manure and reported that most of the loss (83 to 95%) was due to NO$_3^-$ leaching.

6-5. Recommendations

When spring species (barley, wheat and oat) were planted in the third or fourth week of August, the cover crops winter-killed and soil mineral N increased in the root zone relative to that under fallow plots in the spring. Under western Lower Fraser Valley farming system, winter cropping with spring species particularly in situations where summer crops (early potatoes, peas and beans) are harvested in July, may be beneficial not only in protecting soil NO_3^- from leaching during winter but also synchronization of N availability with N uptake for summer crops.

It was evident from this study that when winter rye was planted in the third week of August (especially under high autumn soil N content), it was highly susceptible to freezing damage. This resulted in decrease during winter of the N taken up before winter leaching period without significantly affecting spring soil mineral N. Thus, despite the fact that August-planting increases N uptake relative to September-planting, the role of winter species in conserving autumn soil N during winter may be limited to situations where summer crops (for example corn) are harvested late in the season.

Chapter 7: CONCLUSIONS AND FUTURE RESEARCH

7-1. Conclusions

7-1.1. Cover crop and soil mineral nitrogen before winter leaching

(1) Cover crops that were planted in the third or fourth week of August showed greater potential to produce higher biomass, accumulate larger amounts of N and reduce soil mineral N compared to those that were planted in the third or fourth week of September. Cover crops that were planted in August were also more efficient in absorbing fertilizer N.

(2) In the first two seasons, spring barley and winter rye were similar in terms of biomass production and N uptake, despite great differences in growth stages. Crop species differences in productivity and N accumulation were evident in the 1993-94 season. Cover crops produced higher biomass and accumulated greater amounts of N compared with chickweed (*Stellaria media* L.) in fallow plots. Spring wheat and spring oat were superior to spring barley in terms of biomass production and N uptake. Winter rye and annual ryegrass were equally effective in productivity and N uptake. Generally, winter relative to spring species absorbed greater amounts of autumn residual mineral N, despite less biomass production than by spring species.

7-1.2. Cover crop and soil mineral nitrogen after winter leaching

(1) Despite winter-killing at the start of winter, August-planted spring species may play a positive role in the cycling of autumn residual mineral N. Planting of spring species in the third or fourth week of August results not only in greater biomass production and N accumulation before winter leaching period relative to planting one month later but also in an increase (relative to amount in fallow plots) of root zone soil mineral N in the spring. This was attributed to

mineralization of residue N in early spring. The mineralized N may be readily available and be synchronized with N uptake by the next crop.

(2) The data consistently shows that while winter species growth is vigorous in early spring, only a small amount of net N uptake occurs between late November and spring. This may be attributed to a combination of NO_3^- leaching, denitrification and immobilization during winter and may imply that high mineral N content in the root zone at the start of winter under cover cropping may still lead to great losses of mineral N (mainly NO_3^-) during winter under western Lower Fraser Valley mild weather and fine-textured soils.

(3) August-planting of winter rye may not always be beneficial in terms of N conservation depending on late summer weather conditions. When winter rye is planted in the third or fourth week of August, its growth is greatly enhanced by long days and warmer temperatures in late summer, rendering the crop susceptible to freezing damage. This reduces plant density and hence the amount of N retained during the winter, without significantly affecting spring soil mineral N in the 0-60 cm layer. Winter rye materials in this study that were damaged by freezing, decomposed rapidly in a similar manner to September-planted spring barley that winter-killed at the beginning of winter. This observation was based on visual disappearance of residues and may indicate loss through NO_3^- leaching, denitrification and immobilization during winter.

(4) The biomass increase of winter cover crops between late November and spring of the next year was accompanied by a small increase in N accumulation. Winter-killed spring species residue greatly declined in biomass and N that was assimilated prior to winter, most likely through leaching of soluble organic compounds and decomposition of the residue. For August-planted crops, this decrease over the winter was accompanied by an increase in soil mineral N (0-60 cm) content relative to that in fallow plots in the spring.

(5) While drastic decreases in accumulated N of spring species that were planted in the third or fourth week of August was associated with an increase in soil mineral N in the spring in 0-60 cm layer, the small increase in cover crop N uptake of winter species does not explain the decrease in soil mineral N over the 20-week period, starting late November. This indicates that the main NO_3^- leaching period precedes both spring species residue N mineralization and N uptake by winter species in the spring, suggesting retention of N accumulated by spring species. The small increase in N uptake by winter species may be caused by low soil mineral N concentrations in the spring.

(6) Planting of spring species in August as compared to a month later significantly increased the potential of the cover crops to retain accumulated N during winter.

7-1.3. Spring species nitrogen fractions at winter-kill

(1) Most of the N in autumn-planted spring species was in the organic form indicating most of the mineral N taken up by the cover crops prior to winter was assimilated. A significant proportion of the assimilated N was associated with proteins (cold-water insoluble and soluble). There were some indications of retention of the soluble protein N fraction by the winter-killed spring species. Cover crop NO_3^- content, which can readily leach out of the crop residues after winter-kill, represented a small fraction of the total N ($\sim$ 15%) and at maximum amounted to about 20 kg N ha^{-1} when the cover crops were planted in August and autumn soil mineral N content in the 0-60 cm layer was 200 kg ha^{-1}. The loss of N accumulated by spring species through leaching as NO_3^--N following winter-kill may contribute little to the N leached out of the plant residues and ultimately to the overall leaching out of the root zone during winter. The proportion of NH_4^+-N in the spring species was small and averaged only 3% of total N.

The role of winter species, especially winter rye and annual ryegrass in conserving soil mineral N during winter, has been widely researched. It is evident from this study that autumn-planted spring species can be integrated into winter cropping systems on western Lower Fraser Valley soils. When planted in August, it is apparent that spring species can effectively retain the N taken up before winter-kill and release it to the next crop through mineralization.

7-2. Future research

In three consecutive winter cropping seasons, I found that on the fine-textured soils of western Lower Fraser Valley, spring barley that was planted in the third or fourth week of August can accumulate between 105 and 138 kg N ha^{-1} prior to winter at high (N-100) autumn soil mineral N content. Spring wheat and oat in the third year accumulated about 163 and 143 kg N ha^{-1}, respectively. In all the three seasons, these amounts were reflected in soil mineral N measurements made in spring. This suggests that the residues of these cover crops can retain accumulated N following winter-kill and readily release it in plant available form (NH_4^+ and NO_3^-) in spring through decomposition and mineralization. This result can be confirmed by using ^{15}N labelled plant materials at the start of winter with more frequent sampling for biomass and total N remaining, and soil mineral N content following winter-kill. Alternatively, adequate soil and plant data base can be generated before and after winter leaching on different soil types over several years, and correlation analysis used to associate either biomass production or N accumulation at winter-kill with increase in soil mineral N due to crop residue in the spring. The experiments can be designed to include indirect measurements of NO_3^- leaching (with ^{15}N). In this study residue biomass remaining and N retained in the residue by spring time were estimated using meshbags, but more accurate laboratory techniques have been developed recently (Nyamai,

1992; Lefroy et al., 1995) that can be used to accurately study residue breakdown rates and N release from different plant species. This may provide more information on the role of cover cropping with autumn-planted spring species in protecting autumn soil NO_3^- from leaching during winter. Planting dates of spring species should be studied from as early as mid July to represent earliest summer crops removed from the fields in the western Fraser Valley, for example, early potatoes, peas and beans.

The main aim of cover cropping is to maximize mineral N uptake between summer crop harvest and start of winter leaching period. The duration of this period is variable depending on the time of crop harvest. Currently, there is no definitive documentation on the interactions of planting date, seeding rate and planting pattern (e.g broadcast, row and criss-cross planting) of cover crops with N use efficiency. Planting date can be studied in combination with seeding rate and planting pattern to try and economically maximize mineral N removal from soil prior to winter.

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TABLES OF APPENDICES

Table A-1. List of common terms and abbreviations

N	Nitrogen
NH_4^+	Ammonium
NO_3^-	Nitrate
TCA	Trichloroacetic acid
Residual	Amount remaining in soil after main cropping season
D	Planting date
N-0	Autumn residual mineral N only
N-100	Autumn residual mineral N + 100 kg N ha^{-1} applied
PR	Percent reduction in soil mineral N or NO_3^--N
ANR	Apparent fertilizer N recovery
C	Cover crop
PVP	Polyvinylpyrrolidone
PMSF	Phenylmethylsulfonylfluoride
EDTA	Ethylenediaminetetraacetic acid
WIN	Plant cold-water insoluble N fraction
PN	Plant cold-water soluble N fraction
NPN	Plant organic nonprotein N fraction
NN	Plant nitrate N fraction
AN	Plant ammonium N fraction
DM	Dry matter
TN	Total nitrogen
T	Time of sampling
Soil mineral N	$NH_4^+ + NO_3^-$

Table A-2. Cold-water, hot-water and KCl extractable ammonium and nitrate N for spring barley in late November 1992.

Planting date	SOIL N	Ammonium N			Nitrate N		
		CW¶	HW	KCL	CW	HW	KCL
		------- kg ha⁻¹ -------					
August/24/92	0	1.7(±0.1)	2.1	0.6	1.6(±0.2)	2.1	1.7
August/24/92	100	4.3(±0.2)	7.2	2.2	19.2(±3.9)	25.2	17.9
September/22/92	0	1.0(±0.1)	1.7	0.5	3.1(±0.5)	1.7	3.4
September/22/92	100	1.2(±0.1)	0.7	0.5	5.6(±0.4)	5.4	5.8

¶ CW, HW and KCL are cold-water, hot-water and KCl extractable fractions, respectively;

Table A-3. Cold-water, hot-water and KCl extractable ammonium and nitrate N for spring species in late November 1993.

Nitrogen Content	Cover Crop	Ammonium N			Nitrate N		
		CW¶	HW	KCL	CW	HW	KCL
		------- kg ha⁻¹ -------					
0	Barley	2.9(±0.1)	3.8	1.3	18.1(±2.6)	19.6	19.5
0	Wheat	2.9(±0.1)	2.7	1.0	19.0(±0.9)	21.7	21.2
0	Oat	2.9(±0.4)	3.7	1.1	18.4(±4.8)	22.7	18.8
100	Barley	3.3(±0.3)	3.5	1.2	21.7(±2.1)	30.3	21.3
100	Wheat	2.9(±0.3)	3.2	0.7	17.1(±3.2)	20.1	18.5
100	Oat	3.7(±0.3)	3.9	1.1	29.2(±4.2)	33.0	26.9

¶ CW, HW and KCL are cold-water, hot-water and KCl extractable fractions, respectively.

Table A-4. Soil ammonium nitrogen content in late autumn 1991 and in spring 1992.

Planting date	Autumn soil N content	Cover crop	November/21/91 Depth intervals (cm)			April/08/1992 Depth intervals (cm)		
			0-20	0-40	0-60	0-20	0-40	0-60
					kg ha^{-1}			
Aug/24/92	N-0	Fallow	4	8	11	6	13	20
Aug/24/92	N-0	Barley	4	7	11	10	16	23
Aug/24/92	N-0	Rye	4	7	10	7	14	22
Aug/24/92	N-100	Fallow	4	9	12	7	16	24
Aug/24/92	N-100	Barley	6	12	16	8	16	25
Aug/24/92	N-100	Rye	5	8	13	7	15	24
Sep/22/92	N-0	Fallow	2	4	7	9	15	20
Sep/22/92	N-0	Barley	4	6	9	5	21	26
Sep/22/92	N-0	Rye	4	8	11	6	12	18
Sep/22/92	N-100	Fallow	5	10	14	7	13	20
Sep/22/92	N-100	Barley	4	9	13	5	11	18
Sep/22/92	N-100	Rye	5	7	11	5	11	16

Table A-5. Soil ammonium nitrogen content in late autumn 1992 and in spring 1993.

Planting date	Autumn soil N content	Cover crop	November/24/92 Depth intervals (cm)			April/30/1993 Depth intervals (cm)		
			0-20	0-40	0-60	0-20	0-40	0-60
					kg ha^{-1}			
Aug/24/92	N-0	Fallow	3	7	12	9	17	24
Aug/24/92	N-0	Barley	6	10	13	10	22	29
Aug/24/92	N-0	Rye	3	5	8	10	21	33
Aug/24/92	N-100	Fallow	3	5	7	12	21	30
Aug/24/92	N-100	Barley	6	10	13	8	15	23
Aug/24/92	N-100	Rye	3	6	8	11	23	32
Sep/22/92	N-0	Fallow	5	10	16	12	21	29
Sep/22/92	N-0	Barley	8	16	20	8	17	27
Sep/22/92	N-0	Rye	5	12	18	8	16	25
Sep/22/92	N-100	Fallow	6	11	16	9	15	22
Sep/22/92	N-100	Barley	7	13	17	11	19	26
Sep/22/92	N-100	Rye	6	14	18	7	16	23

Table A-6. Soil ammonium nitrogen content in late autumn 1993 and in spring 1994.

Autumn soil N content	Cover crop	November/24/93 Depth intervals (cm)			April/14/1994 Depth intervals (cm)		
		0-20	0-40	0-60	0-20	0-40	0-60
				kg ha^{-1}			
N-0	Fallow	4	9	13	6	11	17
N-0	Barley	6	13	20	4	9	14
N-0	Wheat	6	11	18	4	8	11
N-0	Oat	6	10	15	4	10	19
N-0	Rye	5	10	17	6	12	18
N-0	Ryegrass	6	11	18	6	10	17
N-100	Fallow	6	12	19	8	12	16
N-100	Barley	6	11	18	4	7	12
N-100	Wheat	4	10	15	4	9	14
N-100	Oat	5	9	14	3	7	13
N-100	Rye	6	11	16	4	7	12
N-100	Ryegrass	7	12	20	4	8	14

Table A-7. Soil NO_3^--N exprressed as a proportion (%) of total mineral N (NH_4^+ + NO_3^--N) before winter leaching period in late November 1991.

Cover crop	August planting (Aug/19/91)		September planting (Sep/16/91)	
	N-0	N-100	N-0	N-100
Fallow	86	91	91	92
Spring barley	72	73	73	85
Winter rye	64	80	75	85

Table A-8. Soil NO_3^--N expressed as a proportion (%) of total mineral N (NH_4^+ + NO_3^--N) before winter leaching period in late November 1992.

	August planting (Aug/24/92)		September planting (Sep/22/92)	
Cover crop	N-0	N-100	N-0	N-100
Fallow	90	97	88	93
Spring barley	63	85	76	90
Winter rye	53	84	75	89

Table A-9. Soil NO_3^--N expressed as a proportion (%) of total mineral N (NH_4^+ + NO_3^--N) before winter leaching period in late November 1993.

Cover crop	N-0	N-100
Fallow/chickweed	92	91
Spring barley	79	88
Spring wheat	81	89
Spring oat	85	91
Winter rye	78	87
Annual ryegrass	77	85

Table A-10. Various N fractions and total N determined on 100 mg of plant material to check recovery of N for samples taken at winter-kill (November 24, 1992).

Planting date	Soil N content	WIN	PN	NPN	NN	AN	TFN†	TN§
				%DM				
Aug/24/92	N-0	0.9(±0.01)	2.3(±0.10)	0.3(±0.02)	0.1(±0.01)	0.1(±0.01)	3.6(±0.12)	3.4(±0.04)
Aug/24/92	N-100	1.0(±0.02)	2.7(±0.24)	0.6(±0.14)	0.7(±0.11)	0.2(±0.01)	5.1(±0.11)	4.9(±0.10)
Sep/22/92	N-0	1.1(±0.06)	2.2(±0.16)	0.6(±0.08)	0.4(±0.03)	0.1(±0.01)	4.3(±0.19)	4.3(±0.10)
Sep/22/92	N-100	1.2(±0.06)	2.3(±0.18)	0.7(±0.08)	0.7(±0.04)	0.2(±0.01)	5.1(±0.13)	4.8(±0.12)

§ Total N determined on 100 mg of plant material to include NO_3^-; † Sum of all fractions;

Table A-11. *Various N fractions and total N determined on 100 mg of plant material to check recovery of N for samples taken at winter-kill (November 24, 1993).*

Soil N content	Cover crop	WIN	PN	NPN	NN	AN	TFN†	TN§
					%DM			
N-0	Barley	0.9(±0.05)	0.9(±0.06)	0.9(±0.08)	0.5(±0.07)	0.1(±0.01)	3.3(±0.08)	3.5(±0.14)
N-0	Wheat	1.1(±0.09)	1.0(±0.18)	0.8(±0.06)	0.4(±0.04)	0.1(±0.01)	3.3(±0.18)	3.6(±0.04)
N-0	Oat	0.8(±0.03)	1.6(±0.13)	0.8(±0.14)	0.5(±0.14)	0.1(±0.01)	3.8(±0.11)	3.3(±0.14)
N-100	Barley	1.0(±0.04)	1.6(±0.21)	0.8(±0.12)	0.8(±0.04)	0.1(±0.01)	4.4(±0.14)	3.6(±0.07)
N-100	Wheat	1.0(±0.11)	1.6(±0.16)	0.6(±0.09)	0.4(±0.09)	0.1(±0.01)	3.7(±0.09)	3.7(±0.09)
N-100	Oat	0.9(±0.07)	1.7(±0.12)	0.9(±0.09)	0.8(±0.09)	0.1(±0.02)	4.4(±0.09)	4.0(±0.13)

§ Total N determined on 100 mg of plant material to include NO_3^-; † Sum of all fractions;

Table A-12. Comparison of cold-water (CW) and hot-water (HW) for extraction of protein- and organic nonprotein-N fractions from plant materials.

Extraction method	November/24/1992		November/24/1993	
	Protein-N	Nonprotein-N	Protein-N	Nonprotein-N
	--------------------------------- %TN -------------------------			
CW	75(±4.1)	12(±1.1)	60(±2.1)	22(±2.7)
HW	63(±3.6)	24(±1.3)	58(±1.8)	22(±2.2)
P > T	0.0066	0.0042	0.5119	0.9440

¶ Protein-N was calculated as the sum of the insoluble (WIN) and soluble fraction (PN);

Table A-13. Comparison of cold-water (CW), hot-water (HW) and 2M KCl (KCL) for extraction of NO_3^--N and NH_4^+-N fractions from plant materials.

Extraction method	November/24/1992		November/24/1993	
	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N
	--------------------------------- %TN ----------------------------			
CW	10(±2.9)	3(±0.2)	15(±1.4)	3(±0.2)
HW	10(±2.7)	4(±0.3)	18(±2.0)	3(±0.3)
P > T	0.9138	0.4136	0.1172	0.1747
CW	10(±2.9)	3(±0.2)	15(±1.4)	3(±0.2)
KCL	10(±2.8)	1(±0.2)	16(±1.2)	1(±0.1)
P > T	0.7565	0.0001	0.2566	0.0001

Table A-14. Carbon content (%DM) of cover crops for the 1991-92 and 1992-93 winter cropping seasons.

Planting date	Nitrogen Level	Crop species	Nov/21/91	Apr/08/92	Nov/24/92	Apr/30/93
Aug/19/91	N-0	Barley	44	42	37	40
Aug/19/91	N-0	Rye	42	42	39	42
Aug/19/91	N-100	Barley	43	36	35	41
Aug/19/91	N-100	Rye	39	43	38	42
Sep/16/91	N-0	Barley	40	32	37	40
Sep/16/91	N-0	Rye	39	43	38	41
Sep/16/91	N-100	Barley	40	33	36	40
Sep/16/91	N-100	Rye	39	43	38	42

Table A-15. Carbon content (%DM) of cover crops for the 1993-94 winter cropping seasons.

Nitrogen level	Crop species	Nov/24/93	Apr/14/94
N-0	Chickweed (fallow)	32	35
N-0	Spring barley	38	39
N-0	Spring wheat	39	40
N-0	spring oat	38	40
N-0	Winter rye	39	40
N-0	Annual ryegrass	38	38
N-100	Chickweed (fallow)	30	37
N-100	Spring barley	37	39
N-100	Spring wheat	39	40
N-100	spring oat	37	39
N-100	Winter rye	39	39
N-100	Annual ryegrass	37	38