AN ABSTRACT OF THE THESIS OF

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Neil W. Christensen

Winter wheat is commonly grown in rotation with leguminous and non-leguminous crops in the Willamette Valley. For agronomic, economic, and environmental reasons it is important to understand the influence of previous crops on availability of N and other nutrients.

Objectives of this study were: (1) to evaluate the effects of long-term rotations on winter wheat response to N fertilizer, and (2) to evaluate the use of Plant Root Simulator™ (PRS) probes for measuring soil N mineralization and N availability to winter wheat.

Field experiments were conducted over three growing seasons in plots of 'Stephens' soft white winter wheat at Hyslop farm. Plots receiving 0, 50, 100, 150 and 200 kg N ha^{-1} at Feekes GS 4 were sampled to determine above ground N uptake, grain yield, and grain protein. In spring 1998, PRS probes were placed in 0 kg N ha^{-1} plots and removed at one-week or two-week intervals. In autumn 1998, probes were placed in unfertilized plots and removed at 1-week, 4-week, and 8-week intervals. Probes measured the availability of NH_4^+-N, NO_3^--N, K^+, Ca^{2+}, Mg^{2+}, and PO_4^{3-}-P.

Grain yield and N uptake were greater for wheat following clover as compared to following oats. Three-year average fertilizer equivalent values calculated from N uptake and grain yield data were 44.5 kg N ha^{-1} and 49.0 kg N ha^{-1}, respectively. The similarity of these independent measurements suggest that differences in N availability were the primary reason for the rotation effect.

PRS probes also detected rotational differences in N availability. Average N recovered by probes sampled at 1-week intervals indicated that there was 63% as much NO_3^--N available to wheat following oat as compared to clover. Wheat recovered 64% as much N following oats as compared to clover. This suggests that PRS probes are an effective method for predicting relative amounts of plant available N. PRS probes also detected rotational differences in plant available potassium.

Agronomic responses are useful for assessing the availability of nutrients that are limiting plant growth. PRS probes, on the other hand, are effective for assessing the availability of both limiting and non-limiting nutrients.

Ion Exchange Membranes and Agronomic Responses as Tools for Assessing Nutrient Availability

by

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Steven Earl Salisbury, Author

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Dedicated to my parents

Tim and Karen

Ion Exchange Membranes and Agronomic Responses as Tools for Assessing Nutrient Availability

INTRODUCTION

Nitrogen is typically the most limiting nutrient for winter wheat production in the Willamette Valley of western Oregon. Growers are challenged by agronomic, economic, and environmental considerations related to N fertilizer management. The goal of N management in the Willamette Valley is to maximize profitability by maintaining crop yield and quality while minimizing negative impacts of N on the environment (Sullivan et al., 1999). In order to attain this goal, precise evaluation of the soil's capacity to supply N to the wheat crop is needed.

Recent changes in the industry have increased awareness of the importance of N management in the Willamette Valley. Changes include increased costs of production, rising concern for environmental issues, and recognition of the effects of rotation crops on soil N supply. The increasing cost of production drives growers to find more efficient methods of N fertilizer management, and in turn to reduce the environmental impact. There is also an increasing interest in rotation effects since wheat is commonly grown in rotation with other crops, both leguminous and non-leguminous.

The main objectives of this study were to:

1 - Evaluate effects of long term rotations on agronomic responses of winter wheat to N fertilizer in western Oregon.

2 - Evaluate the use of Plant Root Simulator™ probes for measuring soil N mineralization and uptake by winter wheat in western Oregon.

LITERATURE REVIEW

Soil N status and availability have a significant influence on agricultural productivity. On a global scale, the soil is estimated to embody 2.4 x 10^{11} tons of N (Stevenson, 1982). However, N is present in two forms in the soil. The larger fraction of N in the soil exists in the soil organic matter and is not available for crop uptake. In contrast, inorganic forms of N are available to the plants. The inorganic N pool is substantially smaller than the organic N pool. Research done in England showed that mineral N measured across 106 arable fields was only 76 kg N ha^{-1} in comparison to 7 t ha^{-1} of organic N (Jarvis et al., 1996). This larger pool of organic N can be converted to available mineral N by specific processes that occur within the N cycle.

Nitrogen Mineralization

The N cycle can be divided into gains, losses, and N cycling where there is no gain or loss of N. N losses are a result of volatilization, leaching, and crop uptake. Inputs of N in the soil occur from biological fixation of atmospheric N, precipitation, and the addition of fertilizers. However, a large portion of this N is organic and unavailable for crop use. Mineralization is the process that transforms organic N to ammonia (NH_3) and ammonium (NH_4^+) by means of soil micro-organisms using organic N as a source of energy (Jansson and Persson, 1982).

Mineralization is an integral part of the N cycle that is important to the management of N. Each year in agricultural systems, mineralization converts a percentage of the soil N to plant available inorganic N. Soil organic matter contains about five percent N, and over a single growing season 1 to 4% of the organic N is

mineralized to inorganic N (Havlin et al., 1999). Studies in the Willamette Valley on a Woodburn silt loam suggest that only 1.8 to 2.6% of the N in the SOM and 5% of the N in the wheat residue become available to the wheat plants as mineral N (Christensen, 1999). Research has shown that microorganisms are capable of providing the crop with 40% of its N demand through mineralization (Marumoto et al., 1982).

Many controlling factors are involved in the mineralization of N in soil. Temperature and moisture have a profound impact on mineralization due to the direct influence on biological activity. It has been commonly observed that the net N mineralization rate increases with temperature and becomes less variable at higher temperature (Stanford et al., 1973). Vigil and Kissel (1995) found N mineralization rate to be directly proportional to temperature. In general, with warmer temperature there will be an increase in biological activity. Furthermore, mineralization ceases at freezing temperatures. Therefore, the temperature range that is best suited for mineralization is generally between 0 and 35°C. A large percentage of N mineralization is due to the activities of mesophyllic microorganisms. Optimal temperatures for mesophyllic activity are between 25 and 37°C (Jarvis et al., 1996). In addition to mesophiles, psychrophiles also have an important influence on N mineralization. Psychrophiles are microorganisms that are active at lower temperatures. Psychrophyllic activity is optimal at temperatures below 15°C (Sylvia et al., 1998). Gill et al. (1995) found that in grassland soils 21 to 38% of total net annual mineralization occurred in the period between November and February.

In addition to soil temperature, the soil water content also affects N mineralization. Low soil moisture will limit microbial activity and hence reduce

mineralization. Orchard and Cook (1983) found that soil respiration measurements in wetter soils reflect greater microbial activity than in drier soils. Furthermore, excess soil moisture may not completely stop mineralization, but will greatly reduce the rate of the process due to the decrease in aerobicity. Some bacteria can function under anaerobic conditions, but the mineralization rate is much slower than under aerobic conditions. Initial CO_2 production rates were found to be greater at 60% water-filled pore space (WFPS) than at 90% (Aulakh et al., 1991). At 90% WFPS, aeration begins to become limiting and biological activity is reduced. However, Stanford and Epstein (1974) observed optimum mineralization rates between -0.33 and -0.1 bar where 80 to 90% of the pore space is occupied by water.

Soil texture also affects mineralization by influencing the moisture and aeration status of the soil and the physical distribution of organic materials. Nitrogen mineralization by microorganisms that adsorb to clay surfaces increases with an increase in clay content. Higher clay content in the soil allows for a more efficient transfer of nutrients between microorganisms of following generations (Gregorich et al., 1991). Furthermore, greater than 50% of the variation in N mineralization rate could be explained by the fraction of pores smaller than 1.2μm (Hassink, 1992). Verberne et al. (1990) concluded that a major portion of the soil organic matter susceptible to mineralization is probably located in pores or on surfaces that can not be accessed by microorganisms. This situation would then lead to the theory that net mineralization rates are lower in finer textured soils. On the basis of moisture and aeration, a finer textured soil would have a greater water holding capacity, and under moist conditions would have less aeration.

Aeration and accessibility to mineralizable soil organic matter are increased due to cultivation. Cultivation increases mineralization rates by making the soil organic matter more accessible to degredation (Ballesdent et al., 1990). Different cultivation methods will have a different impact on N mineralization rates due to different strategies of disruption of the soil structure. It has been estimated that approximately an additional 20 kg N ha^{-1} were mineralized after plowing as compared to direct-drilling (Goss et al., 1993). The timing of cultivation also affects N mineralization, thus affecting the availability of NO_3^- for crop uptake, leaching events, or other processes. Delaying cultivation in the fall will reduce the amount of NO_3^- released (Vinten et al., 1992; Stokes et al., 1992). Mineralization of N from buried residues occurred within 100 to 150 days, whereas, mineralization of N from surface residues occurred within 300 to 660 days (Schomberg et al., 1994). Degradation of buried residues is enhanced due to greater water availability. A desirable situation for a grower would be to synchronize crop demand with the mineralization of N, which can be controlled by cultivation. Aulakh et al. (1991) observed that incorporating vetch in the spring before planting a crop could release sufficient inorganic N to supply the crop's needs during early growth. This flush of N is not only controlled by cultivation timing, but also by rotation effect and residue quality.

In the Willamette Valley, winter wheat is commonly grown in rotation with other crops. It is known that crops grown in rotation often yield more than those grown in a monoculture. Crop rotation increases the general root health of crops and can increase nutrient uptake and nutrient use efficiency (Copeland and Crookston, 1992). Because of their ability to fix atmospheric N_2, leguminous crops can improve the soil N fertility

status for succeeding crops (Kuo and Sainju, 1998). It has also been commonly observed that there is an increase in N uptake and yield for crops following a leguminous crop (Decker et al., 1994; Kuo et al., 1996). Whereas non-leguminous crops such as rye or annual ryegrass do not have this capability, and therefore do not increase soil N availability (Kuo et al., 1996; Torbert et al., 1996). In the first year of a two-year study, Torbet et al. (1996) found that the N content in corn plants after Tibbee crimson clover and rye were 55 and 22 kg N ha^{-1}, respectively. In the second growing season, the N content in the corn was 100 and 33 kg N ha^{-1} after the crimson clover and rye, respectively. Furthermore, the crimson clover rotation effect accounted for 16 to 40% of the total yield increase measured in first and second year respectively. In contrast, the corn yield after the rye rotation decreased due the negative effect of N immobilization following the rye.

Rotation effects are strongly influenced by residue quality. Schomberg et al. (1994) mentioned that initial residue quality influences N dynamics, and stressed the importance of considering this influence. The carbon to nitrogen ratio is an important factor in residue quality. Crop rotation adds a variety of residues with different C:N ratios. This is beneficial to the system by balancing the C:N ratio of the SOM. As mentioned earlier, crops following legumes generally have higher yields. This is because legume residues with a low C:N ratio are more prone to quick degradation, and therefore will supply the soil with a larger fraction of mineral N. It has been reported that as the C:N ratio increases the net mineralization decreases (Jarvis et al., 1996). Furthermore, it has been mentioned that C:N ratios are useful predictors of N mineralization. Quemada and Cabrera (1995) concluded that the best predictor for N mineralization were C:N ratio

and the reciprocal of residue N concentration, supporting the argument that residue quality has an important influence on rotation effect.

The N fertilizer requirement for optimal grain yield is generally reduced for a crop that follows a legume as compared to a monoculture (Havlin et al., 1999). Torbert et al. (1996) found this to be true in corn. Their study concluded that the amount of N fertilizer needed for the succeeding crop to maintain its productivity was reduced following a legume. The decrease in N fertilizer requirement was attributable to the N fixing capability of the legume and to the mineralization power of the soil that contains the rich N residue. Qureshi (1999) showed that a Woodburn silt loam in the Willamette Valley supplied winter wheat following crimson clover with an average of 49 kg N ha^{-1} as compared to a 22 kg N ha^{-1} following spring oats. Additional studies on a Woodburn silt loam in the Willamette Valley suggest that N mineralization can provide from 10% to more than 60% of the winter wheat crop's N demand. The challenge to Willamette Valley wheat growers is to accurately measure and estimate the soil's capacity to supply N to the crop (Christensen, 1999).

Several methods have been proposed for quantifying N mineralization. These include laboratory procedures, field methods, and modeling. Each of these methods has advantages and disadvantages in the determination of N mineralization.

Laboratory procedures include both chemical and biological methods. The goal of laboratory methods has been to develop quick routine tests for estimating the pool of mineralizable N that would correlate with field N mineralization (Rice and Havlin, 1994). Several chemical extractants have been used to estimate N mineralization. These include strong acids and bases, neutral salts, and water. Chemical extractants are used because of

their rapid and convenient way to estimate N released by labile SOM (Jarvis et al., 1996). The advantages of chemical extractant methods are relatively rapid and inexpensive results. The biggest problems with these methods are that they have not been well calibrated with field estimates, the chemical extractants are unlikely to imitate a microbiological process, and they do not account for any of the factors that regulate the rate of mineralization in the field (Rice and Havlin, 1994).

Biological methods include short-term and long-term incubations and greenhouse techniques. Incubations can be conducted under aerobic or anaerobic conditions. Advantages of incubations are that they characterize the pool of mineralizable N, and they describe mineralization kinetics. Stanford (1982) found that N mineralization determined from incubations is highly correlated with N uptake in greenhouse experiments. However, Fox and Piekeilek (1984) found that these incubations are not well correlated to N uptake (R^2 = 0.37 to 0.65) from field experiments. Other drawbacks include sample handling and pretreatment effects on mineralization, and the relatively long incubation time (Rice and Havlin, 1994). Greenhouse techniques are a good screening tool, but have limited application to field conditions because they are carried out under controlled conditions, and are poorly correlated with field experiments. Rice and Havlin (1994) report that the long incubation time required for plant growth and analysis is the main disadvantage to greenhouse techniques. In their attempt to study N mineralization dynamics, McKenney et al. (1995) concluded that laboratory methods are at a disadvantage because they cannot fully simulate actual field situations.

Field methods include soil and plant measurements. One of the more common approaches is measurement of changes in the soil NO_3^- test. Increases in residual soil

NO_3^- are often equated with net N mineralization, whereas decreases are ascribed to losses that could have occurred due to denitrification or leaching. One disadvantage to this test is that it does not predict N mineralization after sampling (Rice and Havlin, 1994). Additionally, it is difficult to estimate N mineralization using changes in mineral N because of high spatial variability of the mineral N (Jarvis et al., 1996). Another method is the buried bag technique. This method involves sealing a soil sample in a polyethylene bag and repositioning it back into the soil at the same temperature. The bag is repositioned with minimal change in the soil moisture content and with no risk of an interaction with plants (Gordon et al., 1987). This is a promising method to asses N mineralization in situ. However, it has not been used at length in agricultural systems and needs further development.

Plant N uptake is another common method for assessing N mineralization. Estimation of N mineralization by measuring plant N uptake in the field has proven to be the most precise method, and has often been used to calibrate chemical and biological methods in the laboratory and greenhouse (Rice and Havlin, 1994). Plant N uptake allows for the integration of the soil, plant, and weather dynamics into N mineralization. However, this method also has disadvantages. It is difficult to incorporate plant sampling methods into fertilizer management programs because the sampling usually occurs too late for any adjustments to be made. Furthermore, it requires significant time and labor inputs, it is site and crop specific, and significant year by location interactions are common (Rice and Havlin, 1994).

Another possible technique to quantify N mineralization is modeling. Modeling seems to have considerable potential to make this assessment. However, the many

intricacies of the N cycle make it difficult to include all of the factors that influence N mineralization. Willigen (1991) compared fourteen models and concluded that more complicated models did not result in better estimates of N released by mineralization than the simpler models. Thus, it appears that more development of models is necessary.

Ion Exchange Technology

One of the most promising methods for estimating N mineralization and nutrient availability is ion exchange technology. Ion exchange methodology offers a way to eliminate problems that are innate to chemical extraction procedures. More importantly it provides a technique that is mechanistically related to availability of nutrients to plants. Ion exchangers could lead to refined fertilizer recommendations, which would benefit the growers and the environment of the Willamette Valley.

Ion exchangers are insoluble inorganic or organic synthetic materials that contain labile ions that are capable of exchanging with other ions in the surrounding media (Dorfner, 1991). Ion exchangers are not only capable of exchanging one ion for another, but can retain exchanged ions for as long as desired. Similar characteristics are found in many natural processes, including nutrient uptake by plants.

Ion exchange technology provides many advantages to soil testing. The most significant of those is its mechanistic relation to nutrient availability. Ion diffusion is the primary mechanism that controls nutrient concentration at the plant root surface. Likewise, the quantity of ions accumulated on the ion exchanger is dependent upon ion concentration and rate of ion diffusion (Yang et al., 1991a, 1991b; Yang and Skogley, 1992). By using a method that responds to both ion concentration in solution and the diffusion of ions through soil provides a means to develop useful bioavailability indices

(Skogley and Dobermann, 1996). The relationship between adsorption of ions by exchange resins and soil solution concentration has been found to be highly significant for potassium, phosphorus, sulfur, and ammonium (Skogley, 1994). All of these nutrients are known to be highly dependent upon diffusion for their movement to plant roots. Qian et al. (1992) reported better correlation of plant nutrient uptake with resin strip extractions than with conventional chemical based soil tests.

The better correlation indicates that soil properties that are in direct control of nutrient availability to the plant are also in direct control of the amount of nutrients that are adsorbed by the ion exchanger. These properties include soil temperature and moisture. Soil temperature is directly related to the diffusion of an ion in water. This relationship is expressed by the Stokes-Einstein equation

$$D_l = k_b T / 6\pi r_i \eta \qquad [1]$$

where k_b, T, r_i, and η are the Boltzmann constant, absolute temperature, ionic radius, and water viscosity, respectively. The diffusion of an ion in water and the soil moisture affect the effective diffusion of an ion through the soil. The effective diffusion of an ion through the soil is expressed by the following equation.

$$D_e = D_l \theta f_l dC_l / dC_s \qquad [2]$$

In this equation, D_e is the effective diffusion coefficient in the soil, D_l is the diffusion of an ion in water, θ is the volumetric water content, f_l is the tortuosity factor, and dC_l/dC_s is the reciprocal of the soil buffering capacity (Barber, 1984). Qian and Schoenau (1997) showed that temperature effect on adsorption of N, P, K, and S by buried resin membranes were not significant ($p<0.05$) at temperatures between 10 and 20°C and between 20 and 30°C. However, they did find a significant ($p<0.05$) influence for

temperatures between 4 and 10°C . The effect was more apparent for N and S than for other nutrients. Temperature effects probably reflecting the impact of increasing water viscocity at lower temperatures.

The amount of N, P, K, and S removed by buried resin membrane significantly decreased with decreasing soil moisture (Qian and Schoenau, 1997). This trend is a reflection of the relation between moisture content and diffusion of nutrients. The drier the soil becomes the more tortuous the diffusion path. Soil temperature and moisture both affect the diffusion of nutrients, but also have an impact of nutrient availability through their influence on processes such as mineralization. Because it is exposed to the same factors as a plant root in soil, a resin membrane ion exchanger should be capable of accurately measuring nutrient availability to plants.

Other advantages offered by ion exchange resins include the fact that they are capable of simultaneous extraction of both cations and anions. Also, the simultaneous uptake occurs independent of the charge of the nutrient (Yang et al., 1991). Another advantage is that results are more accurate than standard soil tests. This is because resin measurements are based on the sensitivity of mechanisms that control nutrient availability. Furthermore, sample handling is eliminated which reduces the chance of contamination and error (Skogley, 1994). Using resin membranes simplify soil testing by eliminating steps. Additionally, nutrient release curves for ten soil orders worldwide have been created for a broad range of elements. These curves indicate that this technology will work on all soils worldwide. Therefore, providing the basis for worldwide standardization (Skogley, 1994). Lastly, the cost-effectiveness of this method could be much better in comparison to the traditional soil testing. This would be a result

of reducing labor inputs, chemicals, laboratory equipment, and overall laboratory time. Most importantly, results that are more accurate will be more valuable than traditional methods.

Ion exchange resins have been a valuable development that provide a desirable means of assessing nutrient availability because of their simulation of plant roots taking up nutrients. A recent development in ion exchange technology is a resin membrane encapsulated in a plastic probe known as the Plant Root Simulator™ (PRS™) (Western Ag Innovations, Saskatoon, SK, Canada). The PRS system consists of two types of probes. They are cation and anion exchange probes. The anion exchange resin contains positively charged surface functional groups which attract anions via electrostatic attraction. The cation exchange resin contains negatively charged surface functional groups and will attract cations by the same forces as the anion resin (Schoenau et al., 1993a). The chemical reaction that occurs at the membrane surface is a simple ion exchange.

The resin membrane is found to be chemically stable in many various solvents (Qian and Schoenau, 1997). This ensures that the resin will not be chemically altered by ionic interactions that occur at the surface functional groups. Furthermore, the probes can be recharged after usage and still maintain their chemical integrity. Regeneration of the PRS probes should be done with counterions that have the lowest affinity to the resin. The sodium ion (Na^+) is a good counterion for the cation resin membrane because it has a low affinity for the resin, and it will not interact with calcium carbonate ($CaCO_3$) affecting the adsorption of potassium and ammonium like the hydrogen ion would. In calcareous soils, the hydrogen ion would react with $CaCO_3$, produce carbon dioxide

(CO_2), and result in a large quantity of calcium taken up by the probe. Large quantities of calcium affect the adsorption of potassium and ammonium. The bicarbonate ion (HCO_3^-) is desirable for the anion resin because this ion displaced into the soil somewhat simulates the HCO_3^- produced in the rhizosphere due to the respiration of microorganisms and plant roots (Qian and Schoenau, 1997).

The PRS probe, like other ion exchange devices, has an exchange capacity. Greer et al. (1997) measured a supply rate of nitrate in a soil that was high enough to reach the probe's resin capacity over a two-week burial period. The maximum capacity was near 1600 μg NO_3^--N/10 cm^2/2 wk. If the resin capacity is not large enough to sorb all the ions available over the burial time, then it is no longer a sink, but rather a "dynamic exchanger" (Qian and Schoenau, 1997).

PRS probes have been used to assess nutrient availability and supply rate of the soil for N, P, K, and S. The amount of P extracted by the exchange membrane has been proven to be highly correlated with conventional chemical extractants (Schoenau et al, 1993). Furthermore, high correlations between anion exchange probes and the conventional $CaCl_2$ extraction shows that the probe is a better way to predict plant-available S (Schoenau et al., 1993b). These high correlations are possibly due to the ability of the probe to account for both solid phase and solution SO_4^{2-}-S. Furthermore, the probe can account for the soil's variability and ability to supply SO_4^{2-}-S to the root.

Qian et al (1995) conducted a study using the cation probes to assess plant available K. This research provided evidence that the PRS technique was significantly correlated with K extracted by three conventional soil analysis methods. Furthermore, highly significant correlations were found between K uptake by canola and wheat crops

and K recovered by cation exchange membrane. Cation probes were also used to measure the K supply to wheat. Supply rates of less than about 50 μg K/10 cm^2/hr indicated an inadequate K supply. Measurements of soil nutrient supply rates with PRS probes offer a significant advantage over conventional soil test measurements. PRS probes provide a dynamic measure of nutrient supply by including many of the factors that control nutrient availability to the crop (Qian et al., 1997). Conventional soil testing measures the quantity of a nutrient available at the time of sampling, and it does not encompass the factors affecting the availability of the nutrient over a period of time.

PRS probes also offer an avenue to measure N mineralization. When the probes are initially placed in the soil, the ions present in solution around the membrane are sorbed. The probes also sorb nutrient ions that become available by mineralization over time. NO_3^--N sorbed by the probe after a two-week burial was better correlated with N uptake by canola than extractable NO_3^--N measured by a conventional two week incubation (Qian and Schoenau, 1995). The higher correlation is probably due to the ability of the exchange membrane to continually absorb the mineralized N. The PRS probes offer many advantages to measuring nitrogen availability. They incorporate biological, chemical, and physical processes which influence transformation of soil organic N to mineral N, and subsequent diffusion of N to roots. Like plant roots, they also act as a sink for N. Additionally, probes measure the available N supply rate on the basis of an absorbing area, which is similar to N uptake at a root surface (Greer et al., 1997).

PRS probes also offer an effective technique that provide a good index for the differences in soils' N supply capacity as affected by long-term management, such as

crop rotation and fertilization history. Qian and Schoenau (1995) found a higher N mineralization potential in soil that was continuously cropped with alfalfa compared with soil cropped with canola, lentil, and barley. These results are consistent with expected N mineralization potentials for a soil cropped with a legume.

In the Willamette Valley, winter wheat is grown in rotation with various crops, including legumes. The residual soil N varies considerably after these different rotations. Growers in the valley are concerned with how much residual N is present and how much will be mineralized during the next growing season. The ability to predict the N supplying power of the soil would be a significant advantage in predicting N fertilizer needs. PRS probes offer an exciting possibility for assessing the soil N supplying power because of their ability to measure crop rotation effects on mineralization, the mechanistic relationship with nutrient availability, and the simplicity of the technique. This approach could ultimately lead to further refinement of fertilizer recommendations and improvement in N fertilizer management.

MATERIALS AND METHODS

Site Description

This study was conducted at Hyslop Farm Oregon State University, Corvallis, Oregon. The plot was located on a Woodburn soil series with the taxonomic classification of fine-silty, mixed, superactive, mesic Aquultic Argixeroll. The experiment was arranged as a randomized complete block split-plot design with crop rotation as the main plots and N fertilizer rates as sub-plots in four blocks. Rotations were 'Stephens' soft white winter wheat following either spring oats, or crimson clover. The five N fertilizer treatments were 0, 50, 100, 150, and 200 kg N ha^{-1}. The rotation treatment plot size was 12m X 45m, and the N fertilizer treatment sub-plot size was 12m X 9m. Rotation plots were established in the 1993-94 growing season, and wheat response data were first collected in the 1995-96 growing season.

Agronomic Trials

Plant tissue samples were taken at approximately Feekes stage 5 and at maturity to estimate dry matter yield and nitrogen uptake. At Feekes stage 5, above ground plant tissue were cut from four 1.5 m lengths of row in each sub-plot. These samples were dried at 70° C in a forced air oven. Samples were then weighed for dry matter yield and ground in a Wiley grinder (Arthur H. Thomas Co., Philadelphia, PA). The samples were then submitted to the Central Analytical Laboratory (CAL) at Oregon State University, Corvallis, Oregon. The N content was determined by Leco CNS 2000 (Leco corporation, St. Joseph, MI) combustion analysis. At maturity, three 1 m lengths of row were sampled from each sub-plot. These samples were weighed to determine dry matter yield. The

samples were threshed, and grain and straw samples were collected. The grain was weighed, ground (Cyclotec 1093 sample mill), and submitted for combustion analysis. The mass of straw was calculated by difference. Samples were dried, ground, and submitted for analysis. Above-ground plant N uptake (kg N ha^{-1}) was calculated by multiplying the N concentration in the straw by the mass of the straw (kg DM ha^{-1}) and adding this to the N concentration in the grain multiplied by the mass of the grain.

Plots were prepared for harvest by initially cutting alleys to eliminate any border effect between treatments. The height of the wheat and the length of the sections to be harvested were measured. The yield plots were harvested with a small plot combine. Harvested grain was cleaned and weighed for yield before determining test weight. Further analysis of the grain included protein and moisture content by whole grain NIR analyzer and 1000 kernel weight.

Ion Exchange Probe Trials

Plant Root Simulator™ (PRS) probes (Western Ag Innovations, Saskatoon, SK, Canada) are thin sheets of ion exchange resin membrane encapsulated in a plastic stake. There are approximately 18cm^2 of ion exchange membrane surface in each probe. They were designed as either anion or cation probes. The anion probes adsorb negatively charged species, and the cation probes adsorb positively charged species.

From March 19 through May 14, 1998, PRS probes were placed in the N control plots (0 kg N ha^{-1}) of wheat following oat or clover at Hyslop Farm. Three cation probes and three anion probes were installed in each wheat after oat and wheat after clover check plot. The probes were spaced about 30-35 cm apart. Anion probes were installed on one side of a row of plants and the cation probes were placed directly opposite on the other

side of the same row. Once the probes were inserted into the soil, they were lightly heeled in to ensure good soil contact.

Initially, two sets of probes were installed (Table 1). One of the sets was removed after one week in the soil. All subsequent sets were removed at two-weeks intervals. Following removal from the soil, each probe was rinsed with deionized water and lightly scrubbed with a toothbrush to remove any adhering soil particles. Probes were then placed in a ziplock freezer bag and taken to the lab for extraction and analysis.

The extraction procedures were outlined in the protocol written by Western Ag Innovations Inc., Saskatoon, Saskatchewan, Canada. Probes were extracted with 0.5 M hydrochloric (HCl) acid. There were 20 ml of HCl delivered (Electrapette, Matrix Technology) for each probe. The extraction period lasted one hour. The probes were then removed from the bag, and the extractant was poured into plastic bottles. Bottles were stored in the refrigerator until analysis. The probes were recharged in a solution of 0.5 M sodium bicarbonate ($NaHCO_3$). Probes soaked in this solution for at least thirty minutes. After thirty minutes the solution was poured out, and fresh $NaHCO_3$ was poured into the 800 ml beaker containing the probes. This process was repeated four times to ensure a thorough recharge of the probes. Once they were recharged, probes were placed in ziplock freezer bags and stored in the refrigerator until re-installment in the field. The extractant was submitted to the CAL for analysis of NH_4^+-N and NO_3^--N by a series 500 Perstorp analytical flow solution analyzer.

From October 29 through December 17, 1998 the probes were again placed in the field to assess the soil's fall nutrient supply capacity (Table 2). The probes were placed in sub-plots that were to receive the 100 kg N ha^{-1} treatment in spring 1999.

Table 1 Sampling schedule for PRS probes, soils, and plants in spring 1998.

Date	Install PRS	Remove PRS	Soil	Plant tissue†
12-Mar	Sets 1 and 2	-	Sampled	-
19-Mar	Set 3	Set 1	-	-
26-Mar	-	Set 2	Sampled	Sampled
2-Apr	Set 4	Set 3	Sampled	Sampled
16-Apr	Set 5	Set 4	Sampled	Sampled
30-Apr	Set 6	Set 5	Sampled	Sampled
14-May	-	Set 6	Sampled	Sampled

†Plant tissue samples taken on February 28 by Qureshi (1999) were used as an early assessment of growth and N concentration.

Table 2 Sampling schedule for PRS probes, soils, and plants in fall 1998.

Date	Install PRS	Remove PRS	Soil	Plant tissue
22-Oct	Sets 1, 9, 11		Sampled	-
29-Oct		Set 1		
30-Oct	Set 2			
5-Nov		Set 2	-	-
6-Nov	Set 3			
12-Nov		Set 3	-	-
13-Nov	Set 4			
19-Nov		Set 4, 9	Sampled	-
20-Nov	Set 5			
26-Nov		Set 5	-	-
27-Nov	Set 6			
3-Dec		Set 6	-	-
4-Dec	Set 7			
10-Dec		Set 7	-	-
11-Dec	Set 8			
17-Dec		Set 8, 10, 11	Sampled	Sampled

Each sub-plot consisted of four drill passes, but one of the inside passes did not receive any fertilizer at planting. This was the drill pass in which the probes were installed. Probes were placed in the unfertilized drill pass so that nutrient assessments could be made without the influence of any fertilizer. Three separate sets of three anion probes and three cation probes were placed in the soil (Table 2). One set remained in the soil for the eight-week duration. Another set was removed after four weeks, and then a second four-week set was installed. The third set was removed every week. Again the probes were placed approximately 30-35 cm apart and were arranged the same way as in spring 1998.

When removed from the soil, all six probes from a plot (3 cation, 3 anion) were placed in the same ziplock freezer bag. The extraction procedures were the same as the spring trials. The only exception was the amount of HCl that was added to each bag. Instead of adding only 20 ml of HCl per bag, 120 ml were transferred to each bag. This amount was determined by the ratio of 20 ml of HCl for each probe. Extractants were analyzed for NH_4^+-N, NO_3^--N, K^+, PO_4^{3-}, Ca^{2+}, and Mg^{2+}. The NH_4^+-N, NO_3^--N, and PO_4^{3-} were analyzed by a series 500 Perstorp analytical flow solution analyzer. The K^+, Ca^{2+}, and Mg^{2+} were analyzed by atomic adsorption spectrophotometer (Perkin-Elmer 4000).

Soil Analysis

In spring 1998, soil samples were taken every two weeks from March 12 to May 14 (Table 1). Eight four-inch deep cores were taken from each plot to make up a composite sample. Samples were immediately dried in a forced-air dryer at 35^0 C or less. The soil was then ground and sieved through a 2 mm stainless steel sieve with a

Dynacrush soil crusher (Custom Laboratory Equipment Co.). The amounts of NH_4^+-N and NO_3^--N were determined using the modified KCl extraction method described by Keeney and Nelson (1982). Twenty-gram samples of the soil were weighed into 250 ml extracting bottles and 75 ml of 2 M KCl were added to each bottle. The bottles were then mechanically shaken for one hour. The extraction solution was filtered through Whitman No. 42 filter paper and analyzed for NH_4^+-N and NO_3^--N by an ALPKEM rapid flow analyzer (RF-300). The NH_4^+-N concentration was determined colorimetrically by forming a complex with salicylate to form indophenol blue. This color was then intensified with sodium nitroprusside and was measured at 660 nm. The NO_3^--N was determined when the nitrate was reduced to nitrite while being passed through a cadmium reactor. Nitrite was then complexed with sulfanilamide and N-(1-Napthyl)-ethylenediamine dihydrochloride to form a red-purple color that was measured at 540 nm.

In fall 1998, soil samples were taken three times (October 29, November 19, December 17) throughout the eight-week field experiment (Table 2). Ten four-inch deep cores were taken to make up a composite sample from each plot. These samples were immediately dried and ground. They were analyzed for inorganic N (NH_4^+-N, NO_3^--N) by the same laboratory methods as in the spring 1998.

In addition, these samples were analyzed for potassium, calcium, magnesium, and phosphate-phosphorus. Potassium, calcium, and magnesium contents were determined by neutral 1N ammonium acetate extraction method. A two-gram sample of soil was weighed into an extracting vessel, and 40 ml of ammonium acetate extracting solution were added to the vessel. Samples were mechanically shaken for 30 minutes and filtered

through Whitman No. 40 filter paper. A 0.5 ml aliquot of the filtrate was then diluted with 12 ml of a lanthanum chloride ($LaCl_3$) and lithium chloride (LiCl) solution (Horneck et al., 1989). This was a 25-fold dilution done with a diluter dispenser (Microlab 500 series, Hamilton Co.). The amount of K^+ was then determined by the atomic adsorption spectrophotometer.

The PO_4^{3-}-P was determined by the dilute acid-fluoride method. Three-gram soil samples were weighed into extracting bottles and 21 ml of the extracting solution was added. The extracting solution contained 0.03 N ammonium fluoride (NH_4F) and 0.0025 N hydrochloric acid (HCl). The bottles were shaken for sixty seconds and filtered immediately using Whatman No. 42 filter paper (Horneck et al., 1989). The concentration of P was determined by using an ALPKEM rapid flow analyzer No. RFA-300.

Additional soil data was also collected each time PRS probes were removed (Table 2). An electronic thermometer (Ingard 420-G) was used weekly to measure the soil temperature at a depth of 10 cm. Volumetric water content of the soil from 0 to 15 cm was measured weekly using Time Domain Reflectometry (TDR) (Trase system I 6050XI). Gravimetric water content was also determined for the first four weeks. Samples were taken from depths of 0 to 15 cm and 0 to 10 cm, weighed, dried at 105^0 C, and weighed again. Gravimetric water content data was used along with volumetric water content data to calculate bulk density of the 0 to 15 cm soil depth.

Plant Analysis

Above ground plant biomass samples were taken at two-week intervals in the spring of 1998. A plant sample collected on February 28 by Qureshi (1999) was also

used for an earlier assessment of plant growth and N concentration. Above ground biomass samples were collected from a 30 cm of row from each plot. They were then oven dried, weighed, and ground. Samples were then submitted to the CAL for combustion analysis to determine total N concentration. The N uptake was calculated by multiplying the percent N in the tissue by the dry matter yield.

In the fall of 1998, only one set of plant samples was taken on December 17 (Table 2). These samples were made up of both above and below ground biomass. A 1 m length of row was dug up from both the unfertilized and fertilized plots in each replication. Soil was carefully washed off plant roots and entire plants were oven-dried, weighed, and ground. A stand count for the 1 m of row was also determined. Plant samples were submitted to the CAL for analysis of N content by the combustion analyzer. Additionally, tissue samples were analyzed for K^+, Ca^{2+}, and Mg^{2+} following digestion by perchloric acid. The carbon in the plant tissue was initially digested with concentrated nitric acid. Digests were allowed to cool to room temperature, and then the concentrated perchloric acid was added to the flask. After the digest was complete the samples were filtered into 100 ml volumetric flask. Cation concentrations were determined by atomic adsorption spectrometry.

Laboratory Analysis

A laboratory experiment was conducted to test the ion exchange capacity of the PRS probes. Five hundred milliliters of a 0.05 M NH_4NO_3 solution were added to each of four 600 ml beakers. One beaker contained ten cation probes, and another contained ten anion probes. In addition, two cation probes were placed in the third beaker containing the NH_4NO_3 solution, and two anion probes were placed in the fourth beaker

containing the solution. One of each type of probe was placed in a check beaker containing deionized water. The probes were allowed to stand in the solution for 24 hours. The probes were then extracted by the same procedures as before. The extractants were drained into plastic bottles and submitted to the CAL for flow solution analysis.

A second experiment was conducted to further analyze the cation probes. In this experiment, a single layer of plastic wrap was tightly placed on top of the beaker. Ten slits, approximately the length of a probe, were cut in the plastic wrap, and the probes were inserted through the slits so that the resin was completely immersed in the solution. The plastic wrap held the probes standing erect in the solution to eliminate possible competition between the probes. They were left in solution for 24 hours. The extraction procedures were consistent with the first experiment. The cation extractant was submitted to the CAL for analysis of NH_4^+-N by flow solution analysis.

Statistical Analysis

All statistical analysis of the data was performed using the MSTAT software program (Michigan State University, East Lansing, MI). Statistical analysis was done using analysis of variance (ANOVA) and least significant difference (LSD) means comparison.

Linear regression analysis of the N uptake and quadratic regression analysis of the grain yield were use to calculate fertilizer equivalent values directly and indirectly, respectively. The intercept value from the wheat after clover rotation equation was substituted as the intercept value for the wheat after oat rotation equation. The wheat after oat equation was then solved for N rate. This value was the fertilizer equivalent value.

RESULTS AND DISCUSSION

Crop Responses to Treatments

Grain Yield

Mean grain yield was greater for wheat following clover than for wheat following oats in each of the three growing seasons. In 1996, the interaction of crop rotation and N rate was not significant, but rotation and N rate treatments independently (P = 0.05) influenced grain yield (Table 3). The grain yield was significantly (P = 0.05) influenced by the interaction of rotation and N fertilizer rate in the 1997 and 1998 growing seasons. Response to N differed over the three growing seasons. In 1996, the mean grain yield was significantly different between rotations receiving less than 150 kg N ha^{-1} (Table 5). Mean grain yields were significantly different between rotations below the 200 kg N ha^{-1} treatment in 1997 (Table 6). In 1998, this difference was only observed below 100 kg N ha^{-1} (Table 7). However, grain yield responded to N in a similar fashion regardless of crop rotation throughout the duration of the study. At low N fertilizer rates, the differences between rotations were much more pronounced than at higher N fertilizer rates (Figures 1, 2, 3). Maximum yield was lower in 1998 (4889 kg ha^{-1}) than in 1996 (5924 kg ha^{-1}) or 1997 (5291 kg ha^{-1}). Additionally, yield of wheat following oats rotation actually exceeded yield of wheat following clover at the 200 kg N ha^{-1} fertilizer rate in 1998 (Table 7, Figure 3).

In 1997, difference in yield due to rotation at the 0 kg N ha^{-1} rate (2271 kg ha^{-1}) was greater than in 1996 (1400 kg ha^{-1}) and 1998 (1572 kg ha^{-1}). This larger difference

Table 3. Analysis of variance of grain yield for the three growing seasons.

		1996		1997		1998	
Source	d.f.	MS	Prob.	MS	Prob.	MS	Prob.
Replication	3	255595	0.2714	295314		147907	0.1712
Rotation	1	8945376	0.0032	27468090	0.0058	354757	0.0650
Error	3	118206		550429		43590	
N-rate	4	34828788	0.0000	36076802	0.0000	13513538	0.0000
R X N	4	410659	0.1970	1828296	0.0000	2001052	0.0005
Error	24	250493		103295		267102	
Total	39						

Table 4. Analysis of variance of grain protein for the three growing seasons.

		1996		1997		1998	
Source	d.f.	MS	Prob.	MS	Prob.	MS	Prob.
Replication	3	0.170		0.274	0.3267	0.086	
Rotation	1	1.541	0.0618	9.216	0.0045	11.610	0.0033
Error	3	0.181		0.155		0.158	
N-rate	4	0.577	0.0000	3.685	0.0000	11.123	0.0000
R X N	4	0.082	0.1499	0.164	0.0224	1.260	0.0000
Error	24	0.044		0.047		0.068	
Total	39						

Table 5. Mean grain yield and protein content of winter wheat for the 1996 growing season.

Total N applied	Yield ---------- kg ha^{-1} ----------		Protein ---------- % ----------	
	Previous crop		Previous crop	
Kg ha^{-1}	clover	oat	clover	oat
0	3697 e	2297 f	8.6 a	8.4 ab
50	5360 d	4106 e	8.3 b	7.8 c
100	6930 c	5792 d	8.4 ab	7.7 c
150	7454 bc	7106 c	8.2 b	7.9 c
200	8543 a	7952 ab	8.7 a	8.4 ab
LSD†	730.4		0.31	
CV (%)	8.5		2.6	

† Means followed by the same letter are not significantly different at the P = 0.05 level.

Table 6. Mean grain yield and protein content of winter wheat for the 1997 growing season.

Total N applied	Yield ---------- kg ha^{-1} ----------		Protein ---------- % ----------	
	Previous crop		Previous crop	
Kg ha^{-1}	clover	oat	clover	oat
0	3407 f	1136 h	8.2 c	7.7 d
50	5306 e	2869 g	8.0 cd	6.9 e
100	6600 c	4842 e	8.2 c	7.2 e
150	7868 a	6080 d	8.9 b	7.9 d
200	7418 ab	7386 b	9.7 a	8.6 b
LSD†	469.0		0.32	
CV (%)	6.1		2.7	

†Means followed by the same letter are not significantly different at the P = 0.05 level.

Table 7. Mean grain yield and protein content of winter wheat for the 1998 growing season.

Total N applied	Yield ---------- kg ha^{-1} ----------		Protein ---------- % ----------	
	Previous crop		Previous crop	
Kg ha^{-1}	clover	oat	clover	oat
0	3559 d	1987 e	7.8 e	7.8 e
50	4943 c	4057 d	7.8 e	7.2 f
100	5440 abc	5723 ab	9.1 c	7.5 ef
150	5621 abc	6031 ab	9.8 b	8.5 d
200	5355 bc	6177 a	11.4 a	9.5 bc
LSD†	754.2		0.38	
CV (%)	10.6		3.0	

†Means followed by the same letter are not significantly different at the P = 0.05 level.

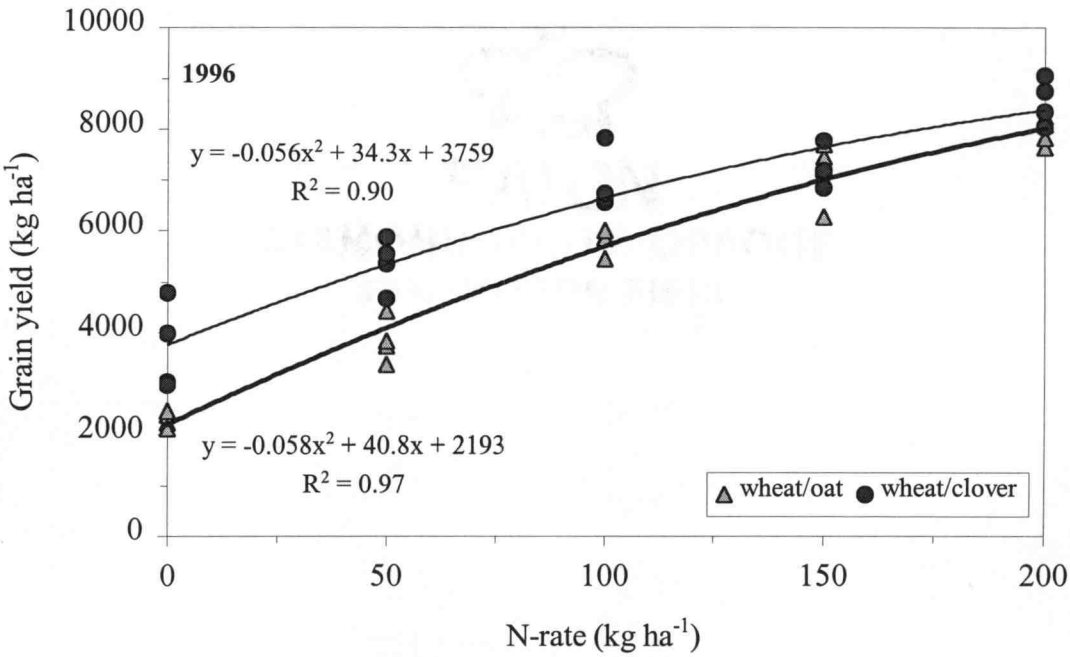

Figure 1. Grain yield response as influenced by N fertilizer rate for winter wheat following oat or clover in the 1996 growing season.

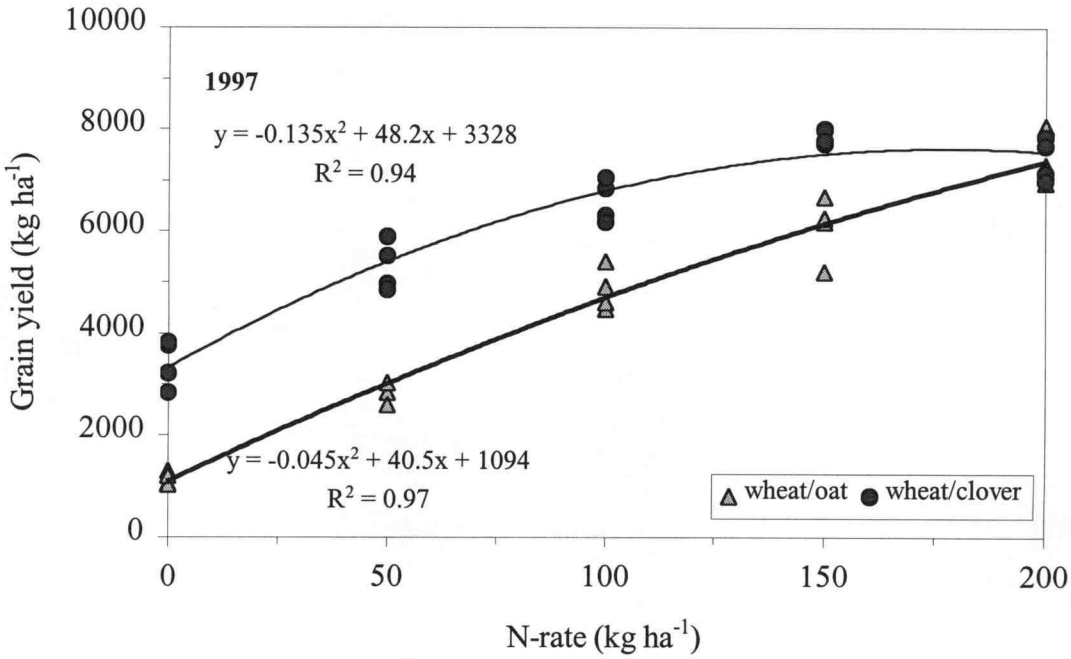

Figure 2. Grain yield response as influenced by N fertilizer rate for winter wheat following oat or clover in the 1997 growing seasons.

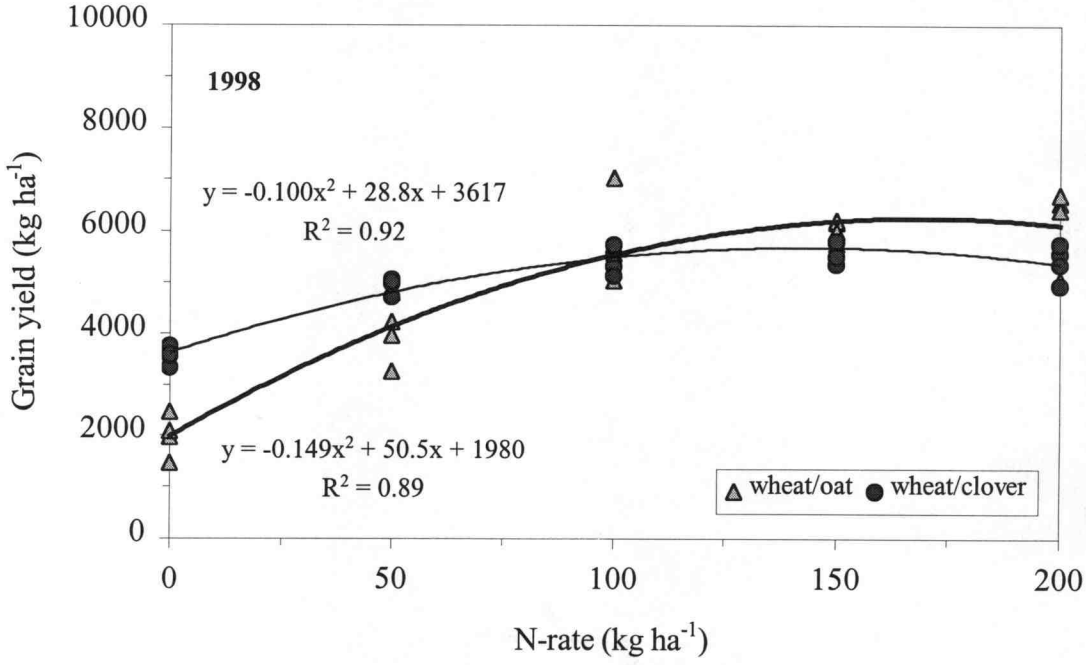

Figure 3. Grain yield response as influenced by N fertilizer rate for winter wheat following oat or clover in the 1998 growing seasons.

in 1997 is attributable to the lack of N fertilizer at planting in fall 1996. Without the N fertilizer at planting, wheat following oats lagged behind wheat following clover in growth, which greatly diminished its N uptake capacity (Qureshi, 1999) and yield in the absence of spring N fertilizer. To avoid this problem in the following year, 20 kg N ha^{-1} were banded with the seed at planting in fall 1997.

Grain yields were much lower in 1998 than in previous years. Lower yields for this growing season were largely due to a major *Septoria* spp. infestation. Climatic conditions were optimal for the establishment of *Septoria* spp. in 1998. This infestation is most likely the reason why wheat following oats performed better at higher N fertilizer rates than did wheat following clover.

Grain Protein

Mean grain protein was consistently higher for the wheat after clover rotation than the wheat following oat in each year (Tables 5, 6, 7). In 1996, the interaction was not significant effect, but in 1997 and 1998 the interaction of rotation and N rate did significantly ($P = 0.05$) influence grain protein content (Table 4). The protein response to N fertilizer rate in 1996 and 1997 illustrated a classic dilution effect (Figures 7 and 8). The protein means at the intermediate N fertilizer rates were significantly lower than the means at the lowest and highest N rates. The highest protein contents were measured in 1998 when yield potential was lower (Figure 9). Maximum yield was attained at approximately 100 kg N ha^{-1} and grain protein increased significantly with each increment of additional N (Table 7). The lower yield potential lead to more nitrogen consumed for protein production. Over the three growing seasons, wheat following

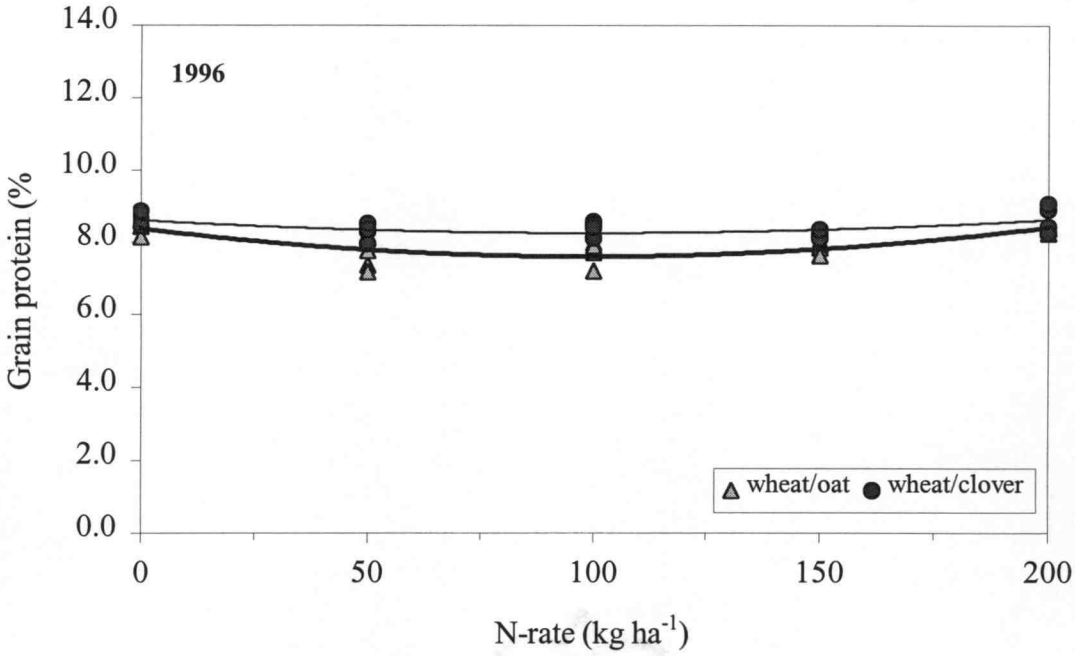

Figure 4. Grain protein for winter wheat grown after oat or clover as influenced by N fertilizer rate from the 1996 growing season.

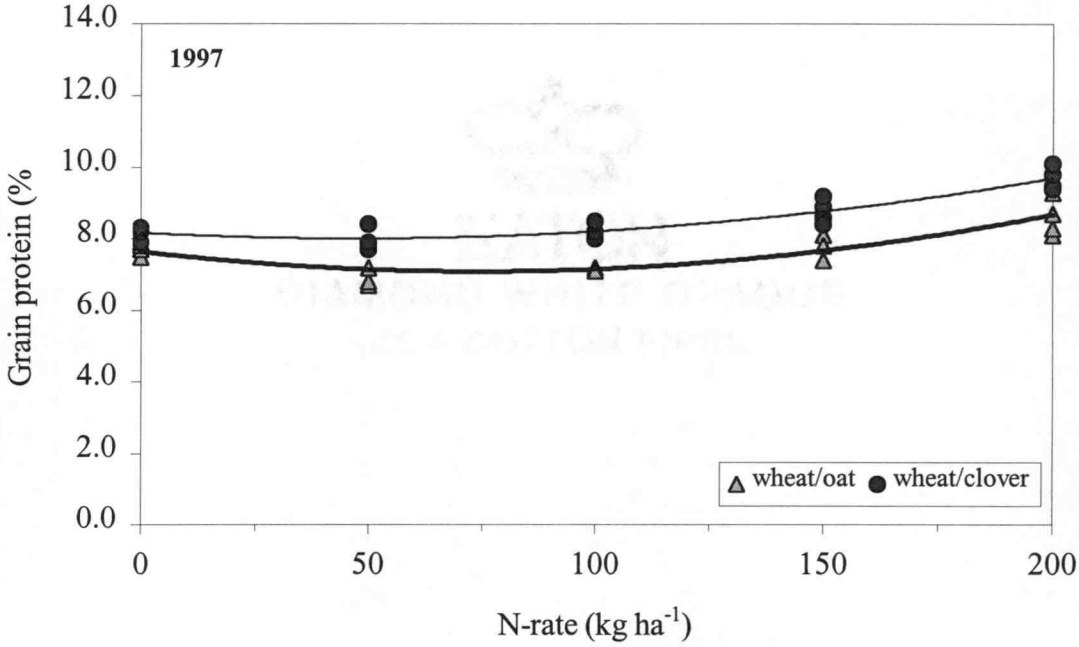

Figure 5. Grain protein for winter wheat grown after oat or clover as influenced by N fertilizer rate from the 1997 growing season.

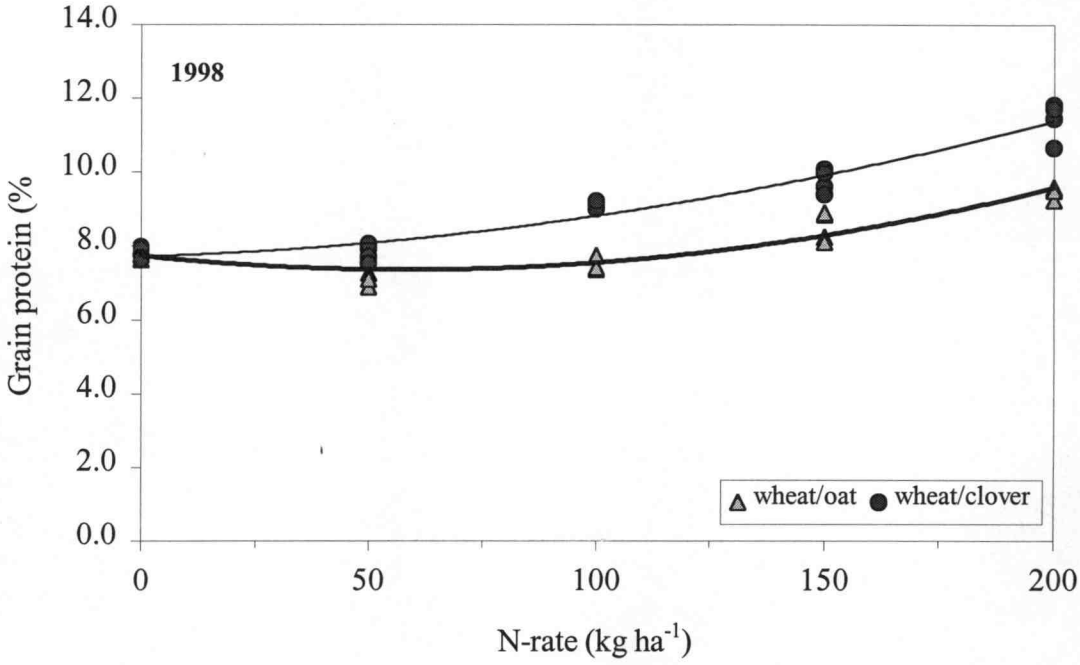

Figure 6. Grain protein for winter wheat grown after oat or clover as influenced by N fertilizer rate from the 1998 growing season.

clover had a significantly (P = 0.05) higher percent protein (8.7%) than the wheat after oat (7.9%).

Total Biomass

The amount of total biomass increased with N fertilizer rate and was consistently greater for wheat after clover than for wheat after oat in 1996 and 1997 (Table 8). However, the difference between rotation was only significant at the lower N fertilizer rates in 1997 and 1998. In 1996, there was no significant difference in the amount of biomass produced by each rotation. The 1997 wheat after clover crop produced significantly more biomass for the treatments less than 150 kg N ha^{-1}. In 1998, total biomass was lower for wheat after oats at 0 and 50 kg N ha^{-1} but highest at 200 kg N ha^{-1}. Total biomass responses to N fertilizer rate were quite similar to the grain yield responses (Figures 4, 5, 6). However, maximum total biomass was not as severely impacted by *Septoria* spp. as was grain yield in 1998.

Nitrogen Uptake

The total N uptake was consistently greater for wheat following clover than for wheat following oats in all three growing seasons (Table 9). Three-year means for the two rotations were significantly different at all N fertilizer rates (Table 10). Over the three growing seasons, mean N uptake by wheat following clover was significantly (P = 0.05) greater (139 kg ha^{-1}) than the wheat after oat (108 kg ha^{-1}). Nitrogen uptake responses illustrate a near parallel relationship between rotations (Figures 10, 11, 12). The nitrogen uptake efficiencies ranged from 59 to 81% and 65 to 79% for the wheat after oat and wheat after clover rotations, respectively. In 1997, the N uptake by

unfertilized wheat after oat was only one-half as much as in 1996 and 1998. This drastic decline was due to the lack of N fertilizer at planting. Qureshi (1999) found that under N deficient conditions, N uptake by winter wheat in the spring can be extremely impaired when no N was applied at planting.

The N uptake in the 0 kg N ha^{-1} plots was substantially greater for wheat following clover. This data highly suggests that clover is indeed supplying wheat with more nitrogen than was supplied by oats. A direct estimate of the fertilizer equivalent value was calculated based on the N uptake measurements. An average of the three years revealed a fertilizer equivalent value of 44.5 kg N ha^{-1}. This value is the amount of N fertilizer needed by the wheat after oat rotation to equal N uptake by wheat following clover. The grain yield also indicates that the clover is supplying more nitrogen to the wheat crop than the oat. An indirect estimate of the fertilizer equivalent value was calculated using the yield measurements. A three-year average revealed a fertilizer equivalent value of 49.0 kg N ha^{-1}. Because these two estimates are independent of one another, their similarity suggests that the differences in nitrogen availability was the primary reason for the rotation effect.

C:N Ratio

The C:N ratios of the wheat residue also indicate that the wheat following clover is assimilating more inorganic nitrogen than the wheat following oat (Table 11). This greater assimilation is related to the higher rate of N uptake, which is due to the higher N content of the leguminous residue. The small C:N ratios for the wheat following oat at 0 kg N ha^{-1} indicate high N concentrations in these plants. However, these smaller ratios

Table 8. Total above ground biomass yield for winter wheat for the 1996, 1997, and 1998 growing seasons.

	Total Biomass					
	Previous crop					
N fertilizer	1996		1997		1998	
rate	Clover	Oat	Clover	Oat	Clover	Oat
kg ha^{-1}	----- kg ha^{-1} -----				----- kg ha^{-1} -----	
0	7140 c	5660 c	9420 c	2965 d	9972 f	5577 g
50	15951 b	9292 c	16726 b	10047 c	14291 d	12029 e
100	15979 b	15836 b	20814 a	17245 b	15703 cd	16683 bc
150	17603 ab	16734 b	21776 a	18620 ab	17055 bc	18277 b
200	21976 a	19741 ab	21479 a	19525 ab	16730 bc	20461 a
LSD†	4559		3157		1858	
CV (%)	21		14		9	

†Means comparisons are made within year and across rotation and N fertilizer rate at the 0.05 significance level.

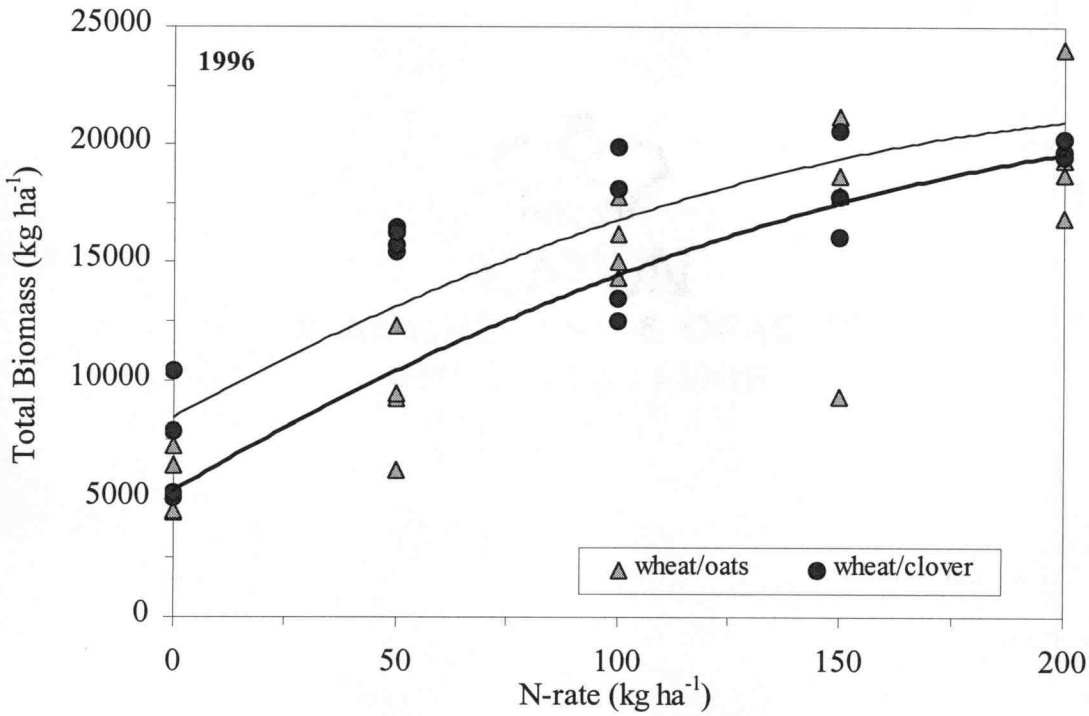

Figure 7. Total biomass response of winter wheat following oat or clover as influenced by N fertilizer rate in the 1996 growing season.

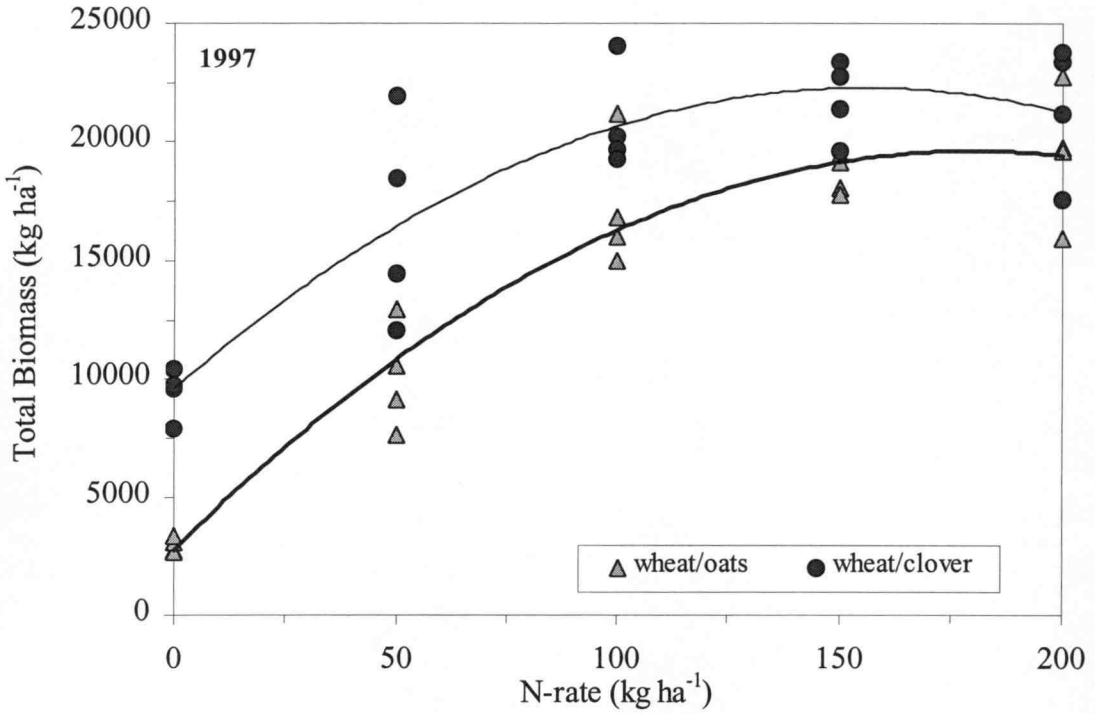

Figure 8. Total biomass response of winter wheat following oat or clover as influenced by N fertilizer rate in the 1997 growing season.

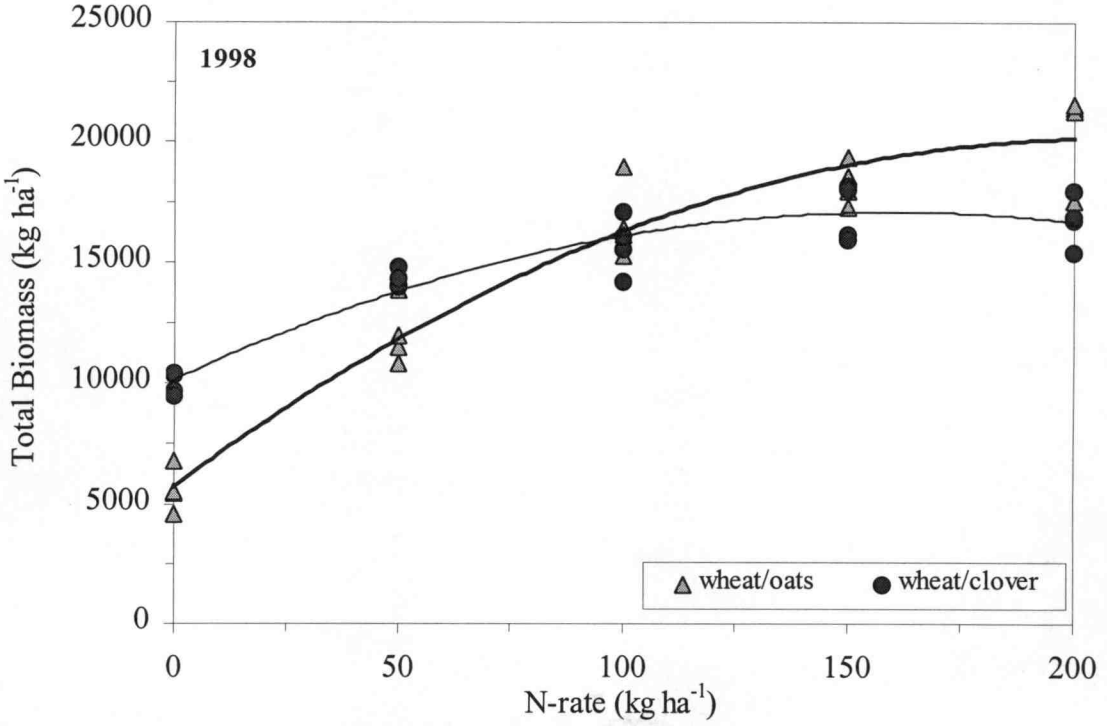

Figure 9. Total biomass response of winter wheat following oat or clover as influenced by N fertilizer rate in the 1998 growing season.

Table 9. Analysis of variance of N uptake by winter wheat over three growing seasons.

Source	d.f.	Sum of Squares	Mean Square	F-value	Probability
Replication	3	910	303	4.81	0.0488
Year	2	7556	3778	59.9	0.0001
Error	6	378	63		
Rotation	1	28333	28333	85.8	0.0000
Year x Rotation	2	1515	757	2.29	0.1566
Error	9	2971	330		
N-rate	4	315054	78764	194.8	0.0000
Year x N-rate	8	5195	649	1.61	0.1381
Rotation x N-rate	4	1936	484	1.2	0.3194
Y x R x N	8	3574	447	1.11	0.3701
Error	72	29106	404		
Total	119	396528			

Table 10. Total N uptake by winter wheat for the 1996, 1997, and 1998 growing seasons.

	Total N-uptake									
	Previous crop									
N fertilizer	Clover					Oat				
rate	1996	1997	1998	average		1996	1997	1998	average	
kg ha^{-1}	----- kg ha^{-1} -----					----- kg ha^{-1} -----				
0	59	57	75	64	f	44	20	44	36	g
50	120	94	110	108	e	64	54	82	67	f
100	133	143	147	142	d	109	101	122	111	e
150	135	168	179	163	c	131	140	164	145	d
200	215	215	216	216	a	159	174	206	180	b
LSD†	38.4	25.5	19.4	16.4		38.4	25.5	19.4	16.4	
CV (%)	22	14	10	16		22	14	10	16	

†Mean comparisons of the 3 year averages are made across rotation and N fertilizer rate at the 0.05 significance level.

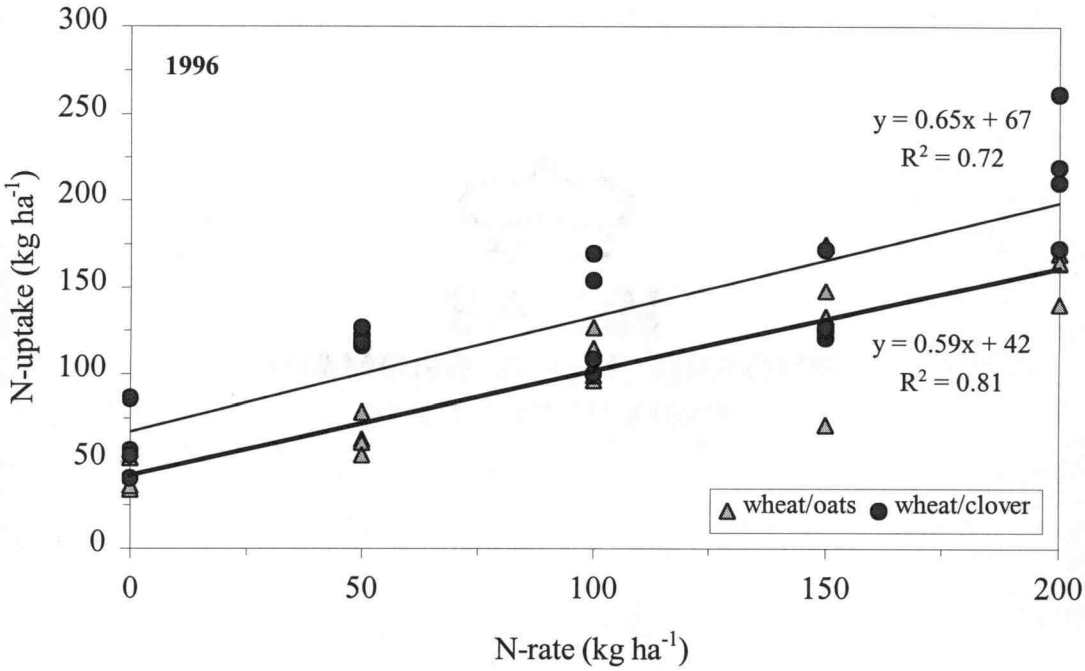

Figure 10. Nitrogen uptake in winter wheat following oat or clover as influenced by N fertilizer rate during the 1996 growing season.

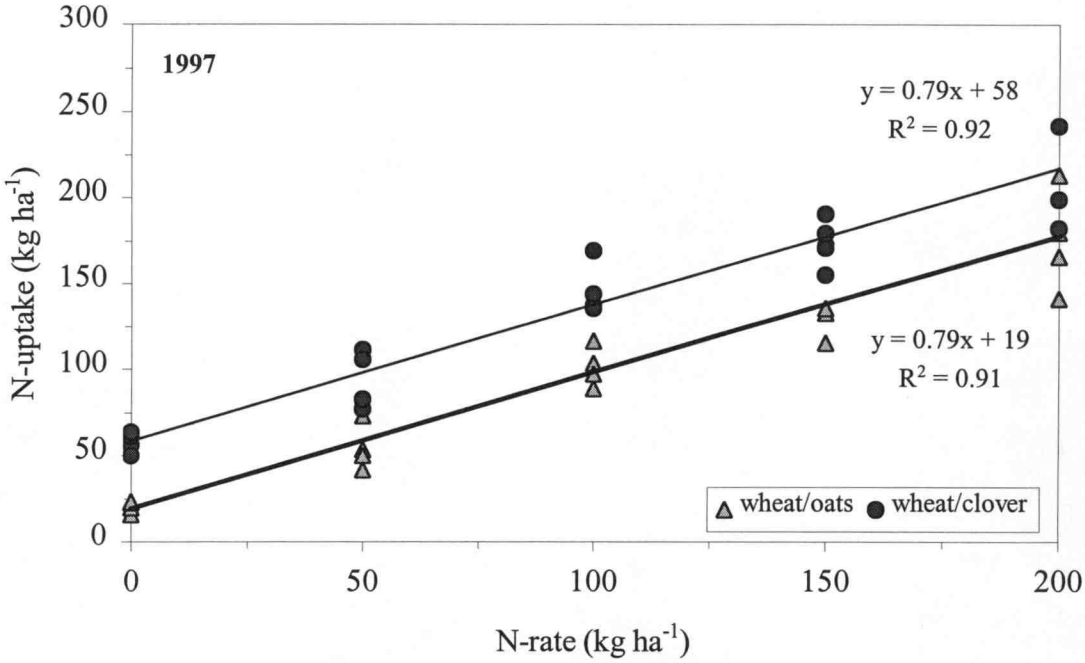

Figure 11. Nitrogen uptake in winter wheat following oat or clover as influenced by N fertilizer rate during the 1997 growing season.

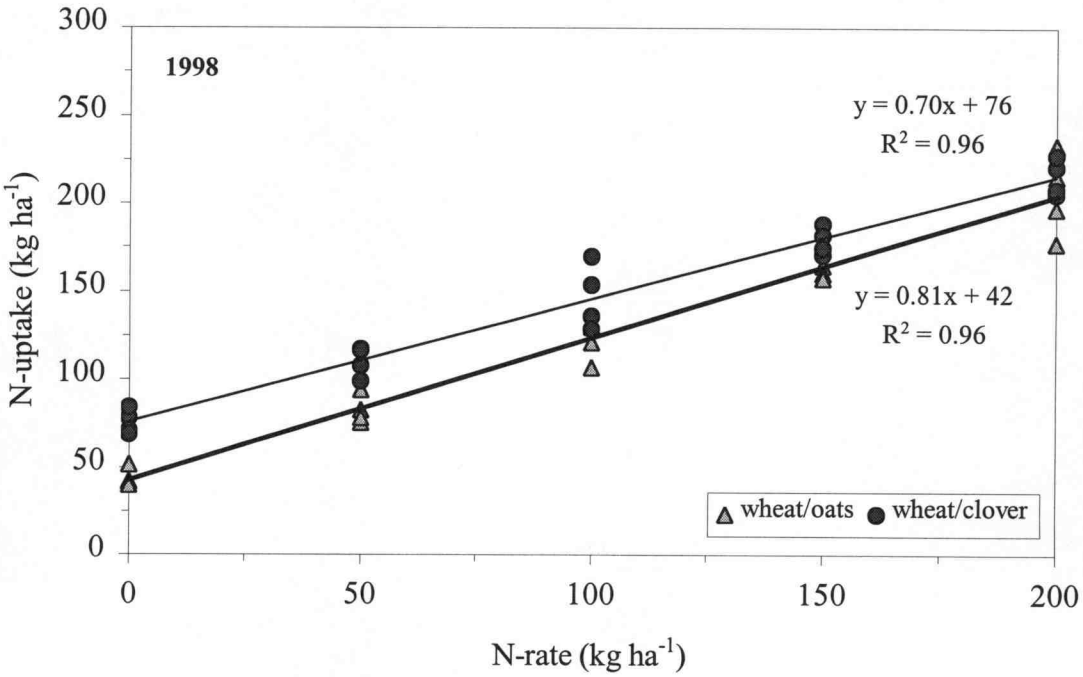

Figure 12. Nitrogen uptake in winter wheat following oat or clover as influenced by N fertilizer rate during the 1998 growing season.

Table 11. C:N ratio of winter wheat residue for the 1996, 1997, and 1998 growing seasons.

	C:N Ratio					
	Previous crop					
N fertilizer	1996		1997		1998	
rate	Clover	Oat	Clover	Oat	Clover	Oat
kg ha^{-1}						
0	175	171	274	181	171	147
50	194	201	282	336	149	190
100	160	209	189	284	101	153
150	165	152	153	262	96	114
200	103	125	104	139	62	89
LSD (0.05)	24		64		18	
CV (%)	10		19		10	

are likely due to the lesser amount of biomass produced in the check plots by the wheat following oat rotation.

Plant, Soil, and PRS Probe Responses

Spring Measurements

Plant Growth and N Uptake

In the spring of the 1998 growing season, wheat following clover was clearly producing more biomass than wheat following oat (Figure 13). The interaction of time and crop rotation significantly influenced the amount of dry material produced. The rotation effects were more pronounced later in the spring. The biomass yielded by wheat after clover was significantly ($P = 0.05$) greater (7956 kg ha^{-1}) than the wheat after oat (3433 kg ha^{-1}). This was a response that was consistent with observations from the previous 2 years.

The greater amount of dry material produced by wheat after clover reflects the enhanced N availability and N uptake following the legume. The N uptake for wheat following clover was significantly ($P = 0.05$) greater (47 kg ha^{-1}) than the uptake by the wheat after oat (24 kg ha^{-1}) (Figure 14). The differences in N uptake between sampling dates were also significant ($P = 0.05$). This difference was not due to the February 18 means, which were calculated from data obtained from Qureshi (1999). ANOVAs were calculated with and without February 18 data and the statistical analysis revealed no difference in the results. Therefore, it was judged acceptable to report the February 18 means.

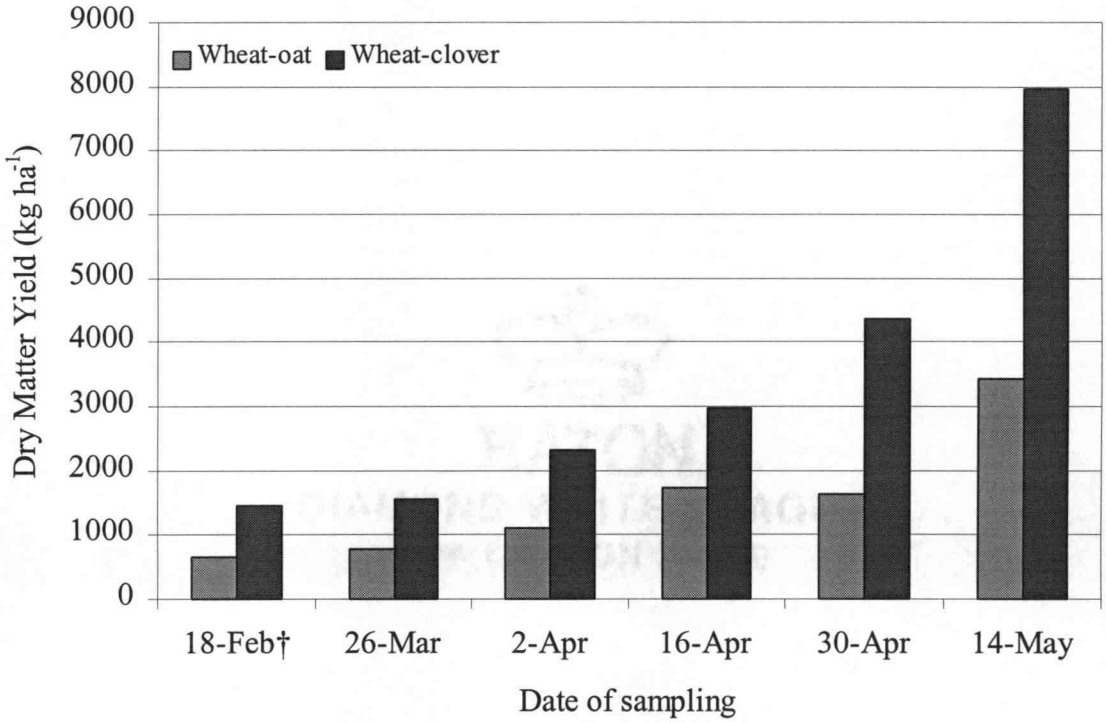

Figure 13. Dry matter yield for winter wheat in spring 1998. The mean dry matter yield was significantly (P = 0.05) less for wheat following oat (1559 kg ha^{-1}) than for wheat following clover (3443 kg ha^{-1}).
†February 18 data was obtained from Qureshi, 1999.

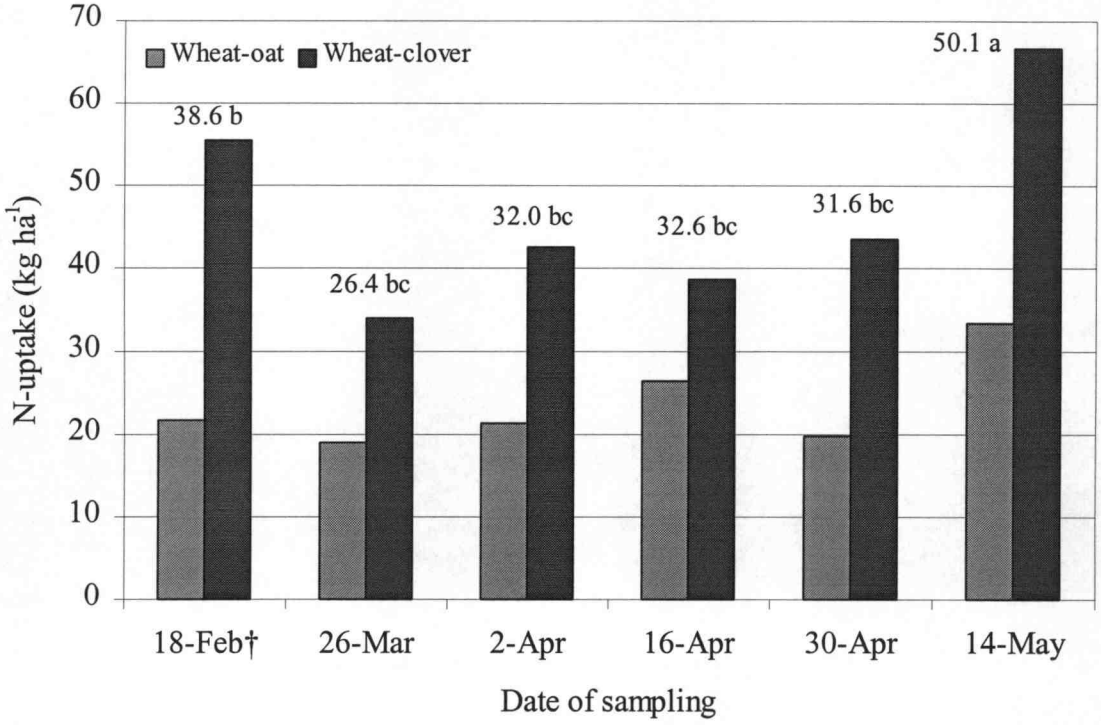

Figure 14. Nitrogen uptake for winter wheat in spring 1998. LSD mean comparison at the 0.05 significance level was performed on the date means. The mean N uptake was significantly (P = 0.05) lower for wheat following oat (24 kg ha^{-1}) than for wheat following clover (47 kg ha^{-1}).
†February 18 data was obtained from Qureshi, 1999.

Table 12. Analysis of variance for NO_3^--N in top four inches of soil measured by a standard soil test in spring 1998.

Source	d.f.	Sum of Squares	Mean Square	F-value	Probability
Replication	3	0.127	0.042	1.23	0.3346
Time	5	4.014	0.803	23.2	0.0000
Error	15	0.519	0.035		
Rotation	1	0.017	0.017	0.321	
Time x Rotation	5	0.022	0.004	0.083	
Error	18	0.946	0.053		
Total	47	5.645			

Table 13. Analysis of variance for NH_4^+-N in top four inches of soil measured by a standard soil test in spring 1998.

Source	d.f.	Sum of Squares	Mean Square	F-value	Probability
Replication	3	8.64	2.88	1.74	0.2024
Time	5	47.47	9.49	5.73	0.0038
Error	15	24.87	1.66		
Rotation	1	0.06	0.06	0.037	
Time x Rotation	5	0.43	0.09	0.53	
Error	18	29.04	1.61		
Total	47	110.52			

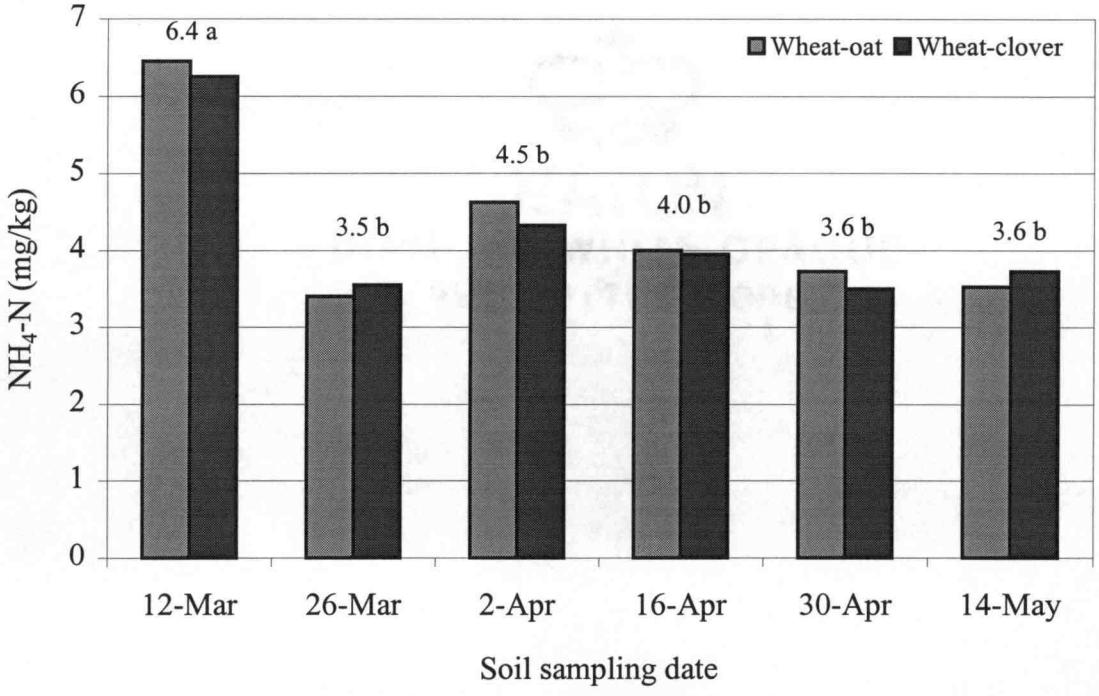

Figure 15. Ammonium nitrogen in the top four inches of soil in spring 1998. LSD mean comparison at the 0.05 significance level was performed on the date means.

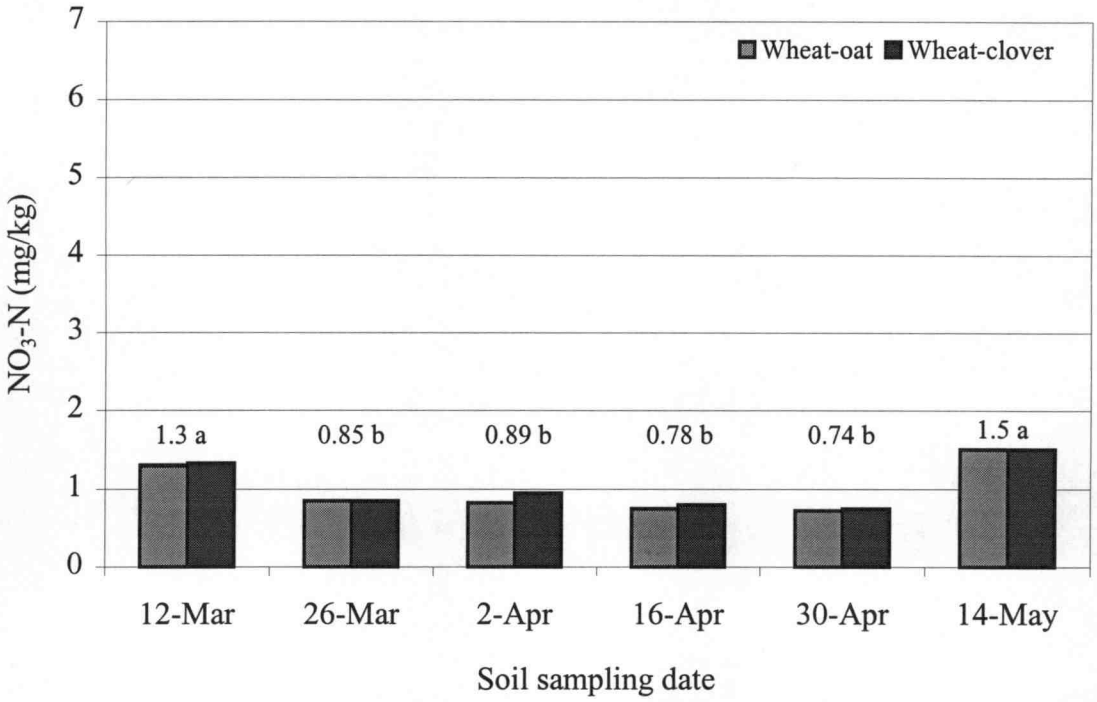

Figure 16. Nitrate nitrogen in the top four inches of soil in spring 1998. LSD mean comparison at the 0.05 significance level was performed on the date means.

Soil Analysis

Standard soil tests for inorganic forms of nitrogen did not show a rotation effect in this spring study (Tables 12 and 13). Both NH_4^+-N and NO_3^--N remained at low and relatively constant levels (Figures 15 and 16). However, a temporal effect was significant in the two forms of nitrogen. The low levels of N are due to the system (0 kg N ha^{-1} treatment plots) being very N deficient. Either very little N was being mineralized in the spring, or when mineralization did occur the N was taken up immediately by the N deficient plants. Little, if any, of the mineralized NH_4^+-N remained to be converted to NO_3^--N by nitrification. Therefore, there was no apparent change in either of the inorganic N levels.

PRS Probe Measurements

Ion exchange resin membranes, in the form of PRS probes, were also used to evaluate N status in the soil. Like standard soil tests for inorganic N, PRS probes did not detect a notable rotation effect on N availability in the spring (Tables 14 and 15, Figures 17 and 18). PRS probes did reveal a significant ($P = 0.05$) temporal effect for NH_4^+-N with considerably more NH_4^+-N recovered on April 2 and 16 (Figure 17). This increase in NH_4^+-N adsorbed by the probes is probably explained by precipitation at the end of March and beginning of April (Figure 19). Since nutrients move to PRS probes solely by diffusion, the soil moisture content can notably influence the diffusion and adsorption of nutrients to the probes. Unlike NH_4^+-N, NO_3^--N recovered from probes did not show a significant temporal effect (Figure 18).

Analysis of the NH_4^+-N and NO_3^--N sorbed by the probes disclosed that no significant difference existed between one-week and two-week samples. Probes that

Table 14. Analysis of variance for NH_4^+-N measured by the PRS probes in the spring of 1998.

Source	d.f.	Sum of Squares	Mean Square	F-Value	Probability
Replication	3	743.3	247.8	0.59	
Time	5	3952.1	790.4	1.90	0.1547
Error	15	6251.8	416.8		
Rotation	1	89.8	89.8	0.22	
Time x Rotation	5	2857.8	571.6	1.38	0.2787
Error	18	7464.8	414.7		
Subsample	2	619.1	309.5	2.35	0.1008
Error	94	12373.3	131.6		
Total	143	34351.9			

Table 15. Analysis of variance for NO_3^--N measured by the PRS probes in the spring of 1998.

Source	d.f.	Sum of Squares	Mean Square	F-Value	Probability
Replication	3	378.8	126.3	1.64	0.2217
Time	5	4590.7	918.1	11.94	0.0001
Error	15	1153	76.9		
Rotation	1	10.3	10.3	0.06	
Time x Rotation	5	644.8	129	0.78	
Error	18	2962.8	164.6		
Subsample	2	696.7	348.3	3.31	0.0407
Error	94	9882.6	105.1		
Total	143	20319.7			

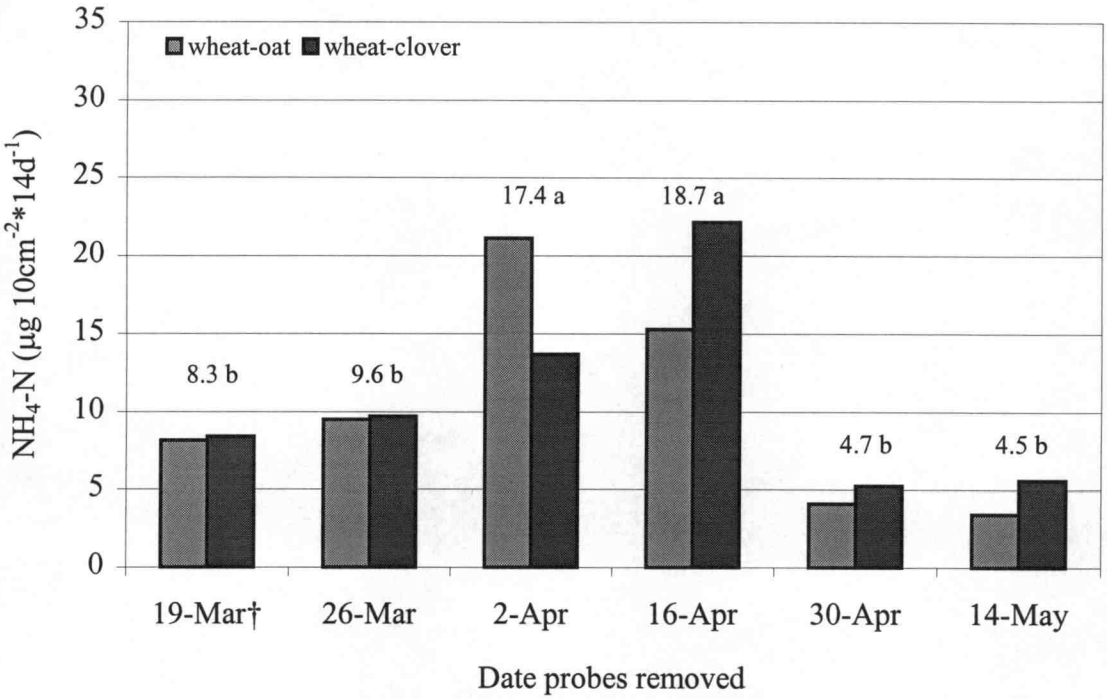

Figure 17. Ammonium nitrogen adsorbed by PRS probes during fourteen-day intervals in spring 1998. LSD mean comparison at the 0.05 significance level was performed on the date means.
†The March 19 set of probes were removed after a seven day interval.

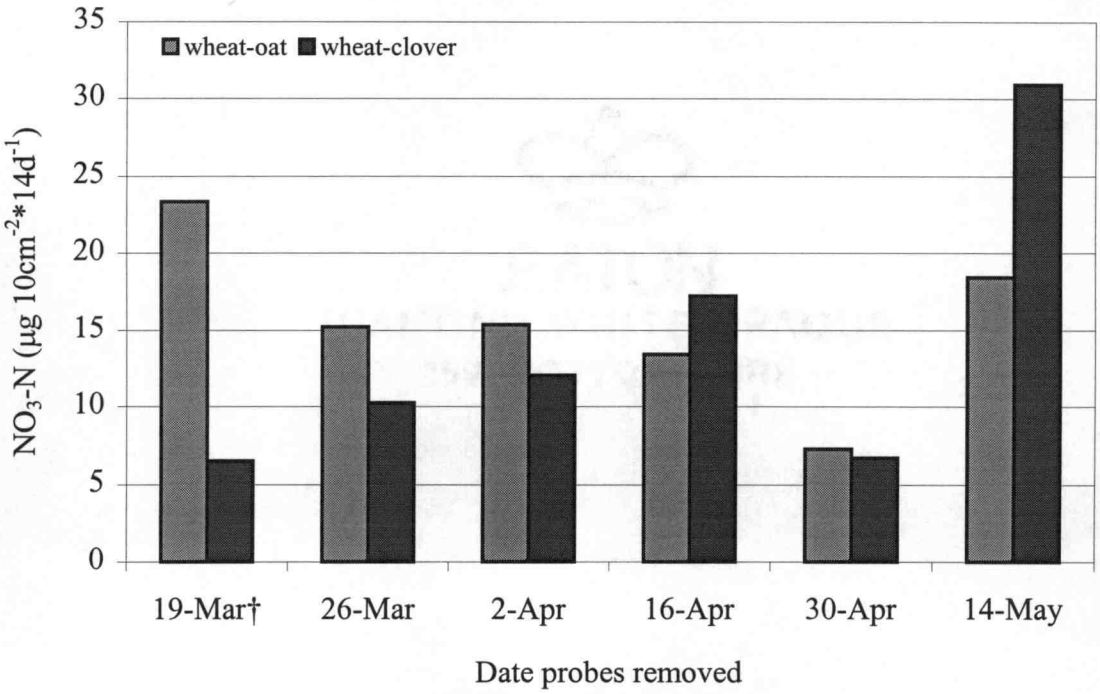

Figure 18. Nitrate nitrogen adsorbed by the PRS probes during fourteen-day intervals in spring 1998.
†The March 19 set of probes were removed after a seven day interval.

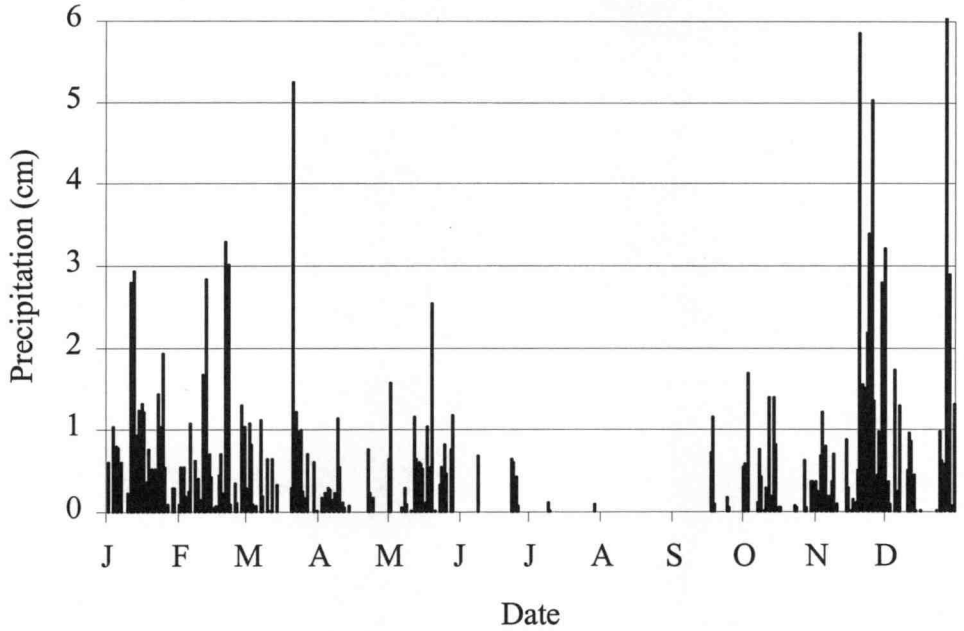

Figure 19. Precipitation measured at Hyslop Farm in 1998.

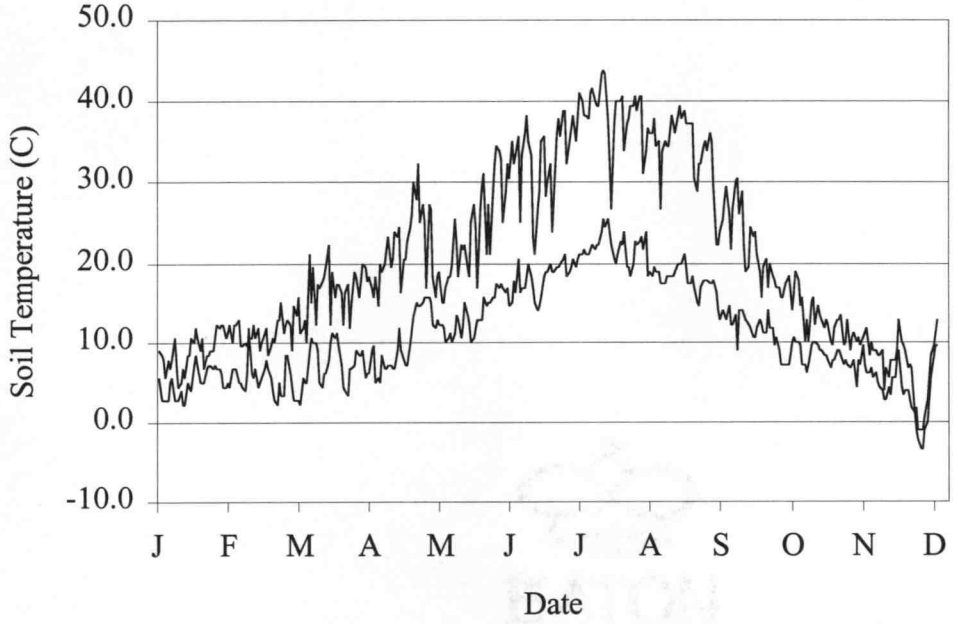

Figure 20. Two-inch soil temperature measurements at Hyslop Farm in 1998.

were removed on March 19 were only in the soil for seven days, yet had adsorbed comparable quantities as probes installed at the same time but removed on March 26. An LSD means comparison of the sampling time shows no significant difference between the two measurements of NH_4^+-N. Similarly, no significant difference was detected in the sampling time for the NO_3^--N measurements.

Individual PRS probes were eluted and analyzed separately in the spring trials. This made it possible to treat data from individual probes as sub-samples in the analysis of variance. Analysis of variance revealed that differences among probes used to measure NH_4^+-N were not significant (Table 14). The analysis of variance for the NO_3^--N measurements showed a significant ($P = 0.05$) difference among probes (Table 15). This most likely does not express differences in probe integrity, but rather spatial differences due to soil heterogeneity.

PRS Probe Exchange Capacity

A laboratory experiment was designed to ensure that the capacities of the PRS probes were large enough to retain larger quantities of nutrients that might be present in the fall. Estimates of the capacities were approximately 2100 μg 10 cm^{-2} for the NH_4^+-N and 400 μg 10 cm^{-2} for the NO_3^--N (Table 16). In the first experiment, the 2 probe per 500 ml treatment showed greater NH_4^+-N retention (2528 μg 10 cm^{-2}) than did the 10 probe treatment (2120 μg 10 cm^{-2}). Concentration of N in the solution after the twenty-four hour trial period was still rather high. This observation confirms that ample nitrogen was available for adsorption by the probes. This difference could have been due to competition between the probes. The issue of competition was further investigated in the second experiment. The amount of NH_4^+-N recovered was very similar to the first

Table 16. Ion exchange capacities of PRS probes as determined by laboratory experiments.

Experiment	Treatment	Species	Capacity (μg N 10 cm^{-2})	C.V. (%)
#1†	10 probes/500ml	NH_4^+	2120	6.25
	10 probes/500ml	NO_3^-	414	6.51
	2 probes/500ml	NH_4^+	2528	
	2 probes/500ml	NO_3^-	392	
#2‡	10 probes/500ml	NH_4^+	2185	5.49

†Ten probes were placed in a beaker containing 500 ml of 0.05M ammonium nitrate solution, and 2 more probes were placed in a separate beaker containing 500 ml of ammonium nitrate. Probes were left in the solution for 24 hours and then eluted.
‡Plastic film was tightly wrapped over the top of the beaker containing 500 ml of 0.05M ammonium nitrate solution. Ten slits were cut in the plastic film, and the probes were inserted through the slits. Probes were left in the solution for 24 hours and then eluted.

experiment. The variability of the cation probes decreased from 6.25% to 5.49% in the second experiment. The variability of the anion probes was similar at 6.51%. It was concluded that the capacities are large enough to handle the levels of nutrients that the probes would encounter in fall measurements.

Fall Measurements

PRS Probe Nitrogen Assessment

PRS cation probes installed for seven day intervals in fall 1998 detected a significant (P = 0.05) difference between the rotations for NH_4^+-N (Figure 21). The probes adsorbed an average of 7.8 μg N 10 cm^{-2} 7 d^{-1} from the wheat after oat rotation as compared to an average of 9.1 μg N 10 cm^{-2} 7 d^{-1} adsorbed from the wheat following clover rotation. A significant (P = 0.05) temporal effect was also detected by the probes.

Similarly, the anion probes installed for seven days detected a significant (P = 0.05) difference between rotations for NO_3^--N (Figure 22). The probes recovered 132 μg N 10 cm^{-2} 7 d^{-1} from the wheat after oat rotation and 207 μg N 10 cm^{-2} 7 d^{-1} from the wheat after clover rotation. Additionally, the probes revealed a significant (P = 0.05) temporal effect in the recovery of soil NO_3^--N (Figure 22). Nitrate recovered by probes was highest during the first two weeks, declined during the second two weeks and was lowest during weeks four through eight. This decline in NO_3^--N was probably not due to uptake by the young wheat seedlings since they were very small with underdeveloped root systems during the eight-week sampling period. Calculations based on N recovery by probes as compared to soil cores suggest that NO_3^--N diffused to probes over distances of less than 2 mm, as compared to a spacing of 230 mm between rows. Since probes

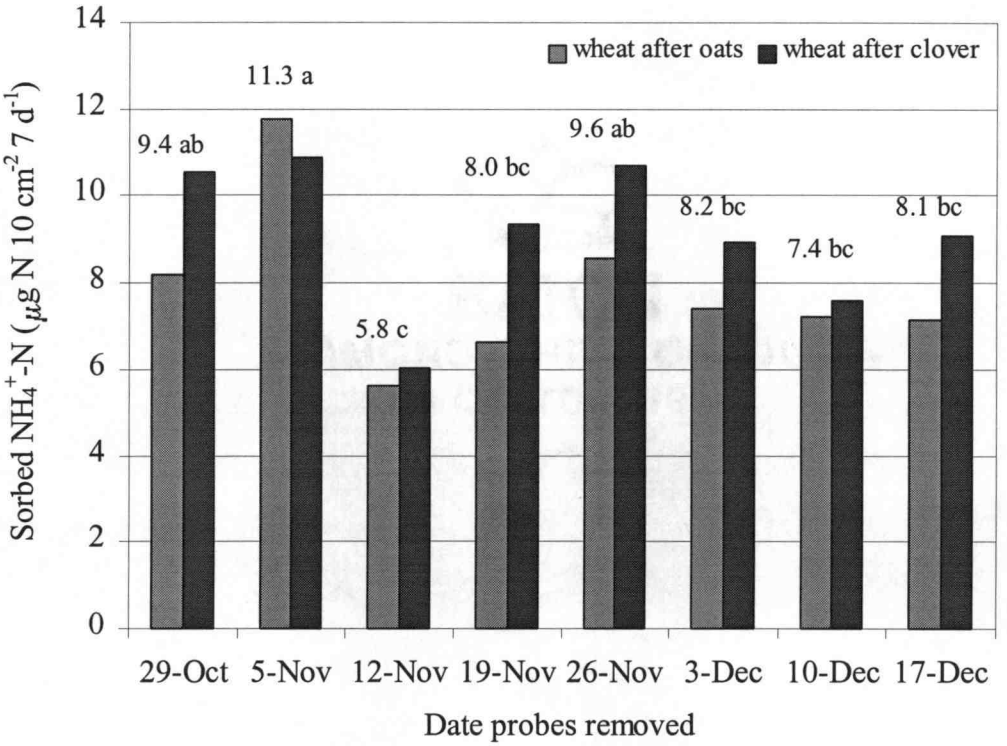

Figure 21. Ammonium nitrogen adsorbed by PRS probes during 7-day intervals in fall 1998. The mean NH_4^+-N adsorbed by PRS probes was significantly less (P = 0.05) for wheat following oat (7.8 μg 10 cm^{-2} 7 d^{-1}) than for wheat following clover (9.1 μg 10 cm^{-2} 7 d^{-1})

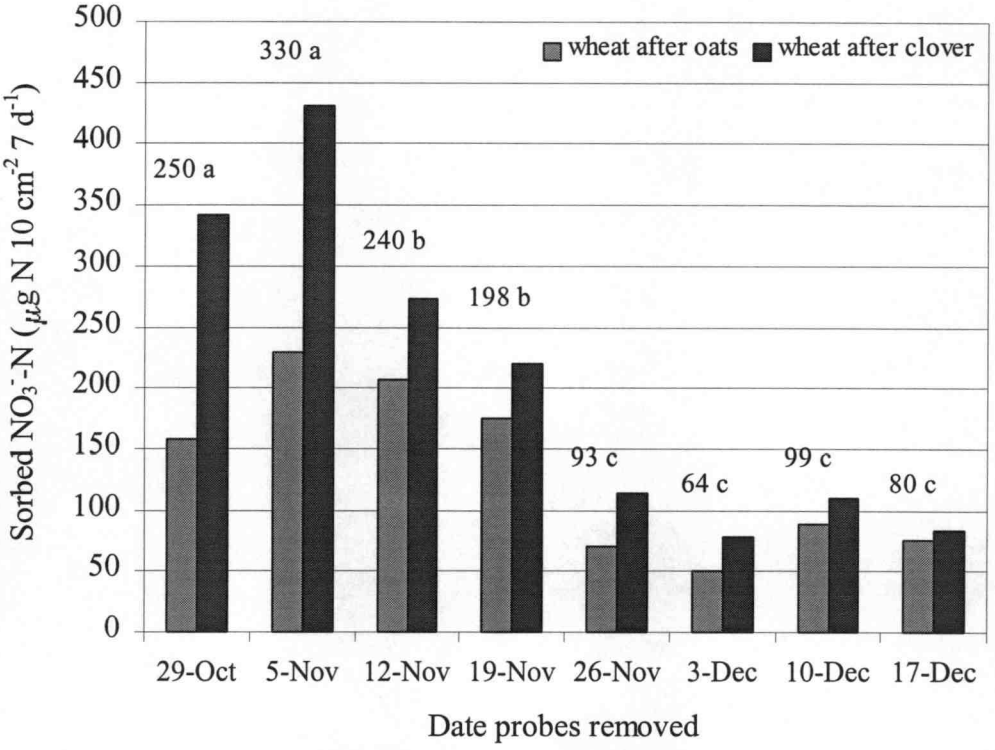

Figure 22. Nitrate nitrogen adsorbed by PRS probes during 7-day intervals in fall 1998. The mean NO_3^--N adsorbed by PRS probes was significantly less (P = 0.05) for wheat following oat (132 µg 10 cm^{-2} 7 d^{-1}) than for wheat following clover (207 µg 10 cm^{-2} 7 d^{-1})

were placed between rows, competition is unlikely to have occurred between plant roots and PRS probes for NO_3^--N diffusion.

The loss of NO_3^--N could have been due to leaching loss or denitrification. Evidence indicates that the loss was most likely due to leaching caused by heavy precipitation, especially during the last four weeks of this eight-week study (Figure 19). The water retention curve for this soil indicates that at 0.1 bar the volumetric water content is 31%. The initial volumetric water content from 0 to 15 cm was an average of 32%. The precipitation (44.1 cm) during the eight week study exceeded the water holding capacity of the soil, therefore allowing the nitrate to be leached.

PRS probes were installed for three different sampling time intervals (1, 4, and 8 weeks). Overall, the probes were capable of detecting a significant ($P = 0.05$) differences between rotation for both NH_4^+-N and NO_3^--N (Table 17). There was no significant difference between sampling time for NH_4^+-N. However, the length of time probes remained in soil significantly ($P = 0.05$) influenced the NO_3^--N measurements. The means show that higher estimates of plant available NO_3^--N were made using the 8-week sampling time as compared to means for the four and one week intervals. When sampling interval means for NO_3^--N are compared to the plant N uptake means, it appears that the 8-week sampling means are an overestimation. The plant N uptake means indicate that the wheat following oat took up 63% as much N as the wheat after clover. One-week means for PRS probes suggest that 64% as much NO_3^--N was present where wheat followed oats as compared to clover. The 4-week means had a slightly larger comparison at 67%, and the 8-week means resulted in a relative comparison of 75% as much diffusible soil NO_3^--N present for wheat after oat as compared to wheat after

Table 17. Eight-week means of NH_4^+-N and NO_3^--N adsorbed by PRS probes as measured by 1-week, 4-week, and 8-week samples, and the mean plant N uptake measured after 8 weeks.

Parameter	Sample interval ‡	Wheat-oat	Wheat-clover	Mean†
		-----μg N 10 cm^{-2}-----		
PRS NH_4^+-N	1-week	8.1	9.4	8.8
	4-week	7.9	12.0	9.9
	8-week	7.1	9.5	8.3
	Mean†	7.7 B	10.3 A	
PRS NO_3^--N	1-week	162	252	207 b
	4-week	236	353	295 b
	8-week	515	685	600 a
	Mean†	304 B	430 A	
Plant N uptake (kg ha^{-1})		6.0 B	9.5 A	

†Means followed by the same letter are not significantly different at P = 0.05 level. Upper case letters refer to rotation means; lower case letters refer to sample interval means.

‡1-week = mean of eight 1-week samples, 4 -week = mean of two 4-week samples, and 8-week = mean of one 8-week sample

clover. Relative comparisons were made with only the NO_3^--N because its availability is more affected by soil and climatic conditions, and it does show a time difference. These data suggests that nitrate adsorbed by PRS probes is a better indicator of plant availability in this situation than is NH_4^+-N. These relative comparisons suggest that the PRS probes estimated the amount of plant available N remarkably well. Additionally, the seven day sampling time seemed to achieve the best estimate for plant available N.

PRS Probe Potassium Assessment

In addition to nitrogen, PRS probes installed for seven day intervals revealed a significant (P = 0.05) rotation effect on potassium (Figure 23). The probes recovered an average of 177 μg K 10 cm^{-2} 7 d^{-1} from the wheat following oat and 260 μg K 10 cm^{-2} 7 d^{-1} from the wheat after clover. A temporal effect was also statistically significant (P = 0.05). The available K increased over time with a peak measurement on November 26 (308 μg K 10 cm^{-2} 7 d^{-1}). This peak measurement was probably due to a substantial rainfall during this sampling interval which resulted in an increase in the volumetric water content of the soil (Figure 24). Consequently, this increased the diffusion of K through the soil and to the probe.

PRS Probe Phosphate-Phosphorus Assessment

The PRS probes installed for seven days also detected a significant (P = 0.05) difference between rotations for phosphate-phosphorus (PO_4^{3-}-P) (Figure 25). In contrast to the rotation effect on K^+, PO_4^{3-}-P recovery by probes was generally greater where wheat followed oats as compared to clover. The mean PO_4^{3-}-P adsorbed in the wheat after oat rotation was 51 μg PO_4^{3-}-P 10 cm^{-2} 7 d^{-1} while the mean PO_4^{3-}-P adsorbed in the

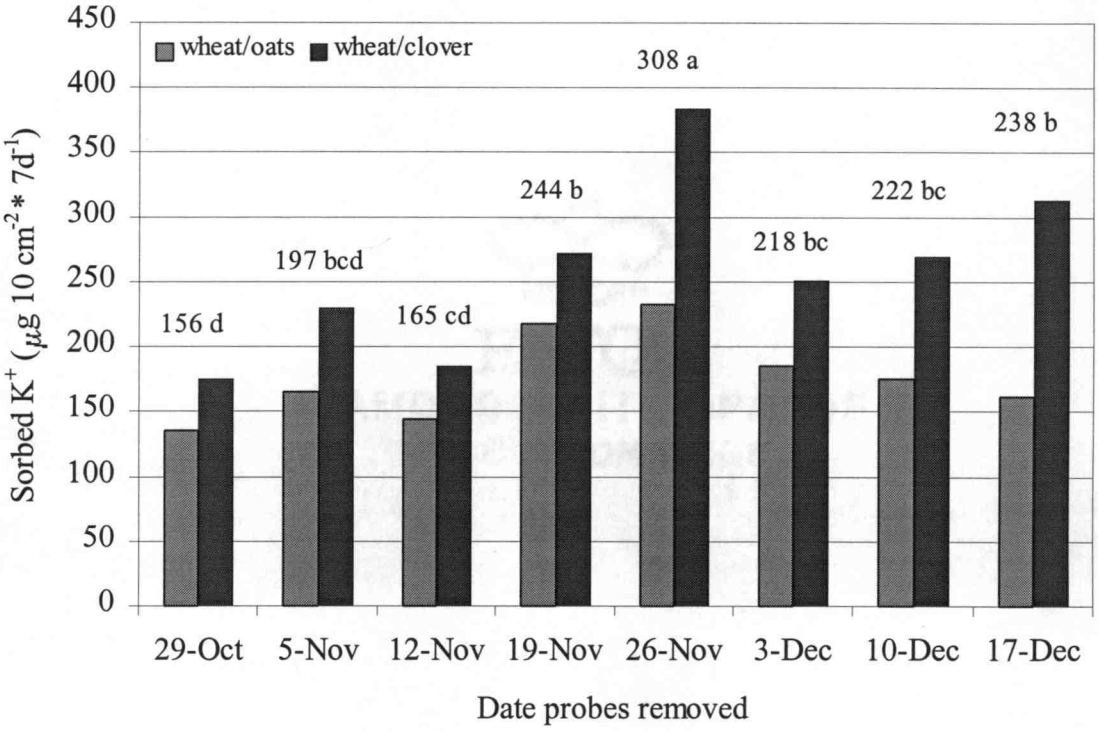

Figure 23. Potassium adsorbed by PRS probes during 7-day intervals in fall 1998. The mean K^+ adsorbed by PRS probes was significantly less (P = 0.05) for wheat following oat (177 µg 10 cm^{-2} 7 d^{-1}) than for wheat following clover (260 µg 10 cm^{-2} 7 d^{-1})

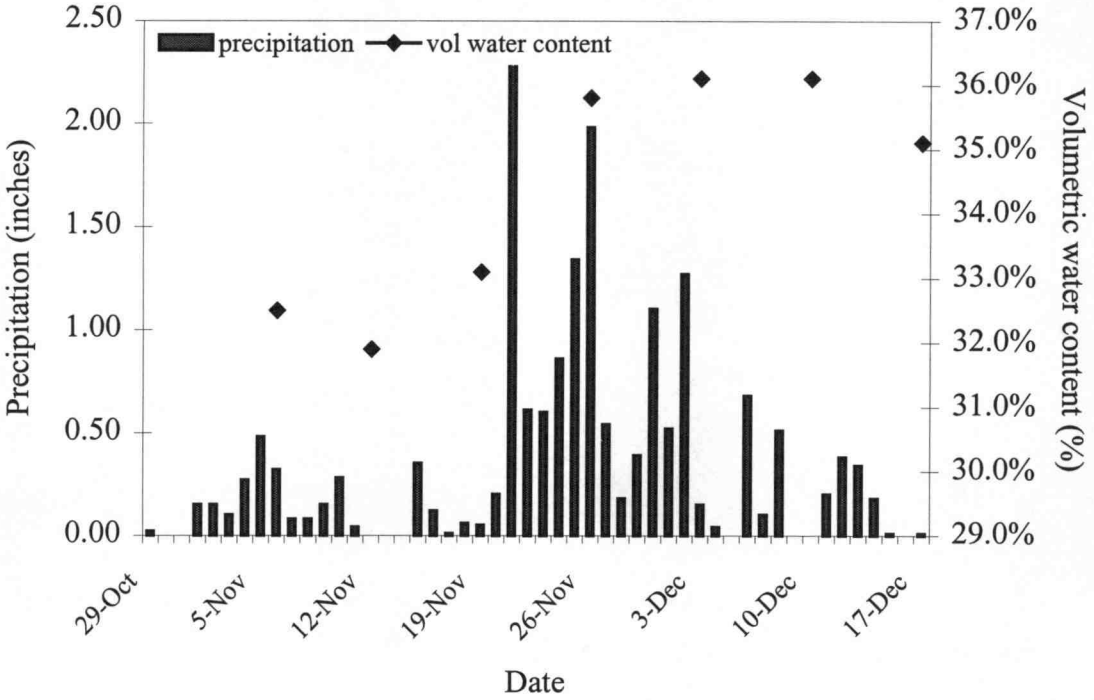

Figure 24. Daily precipitation and weekly soil volumetric water content measured in fall 1998.

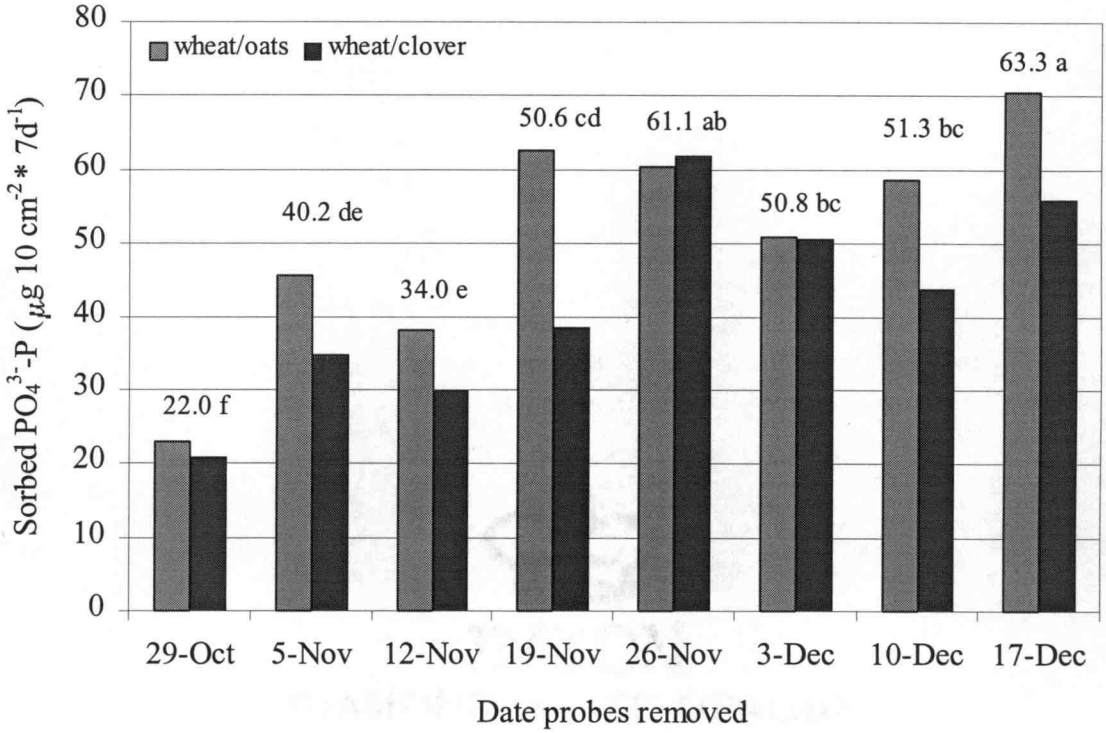

Figure 25. Phosphate-phosphorus adsorbed by PRS probes during 7-day intervals in fall 1998. The mean PO_4^{3-}-P adsorbed by PRS probes was significantly less (P = 0.05) for wheat following clover (42 μg 10 cm^{-2} 7 d^{-1}) than for wheat following oat (51 μg 10 cm^{-2} 7 d^{-1})

wheat following clover was 42 μg PO_4^{3-}-P 10 cm^{-2} 7 d^{-1}. There was also a significant (P = 0.05) temporal effect on PO_4^{3-}-P with higher recovery in the later sample intervals when volumetric water content was higher.

PRS Probe Calcium and Magnesium Assessment

Calcium and magnesium were also measured by the probes. Probes installed for seven days revealed a significant (P = 0.05) temporal effect for both of the divalent cations (Figures 26 and 27). PRS probe adsorption of both cations increased later in the season and appeared to peak around the end of November and early December. There was not a significant rotation effect.

PRS Probe Sampling Interval Comparisons

Comparisons among the three different probe sampling intervals were also made for cations (Table 18). Overall, the PRS probes indicated a significant (P = 0.10) rotation effect for K. The plant K concentration and uptake were also significantly (P = 0.10) influenced by the rotation. The difference in K uptake is due to both the increased K concentration in the plants and the growth response by wheat to increased availability of N following clover.

Comparisons of the probe sampling time intervals for calcium and magnesium were also made (Table 18). The PRS probes indicated that the availability of the divalent cations was unaffected by rotation. Plant concentrations of calcium and magnesium were not statistically different, but uptake was increased because of the growth response to N where wheat followed clover. However, unlike K, PRS probes recovered significantly (P = 0.10) more calcium and magnesium the longer they were left in the soil. Comparisons

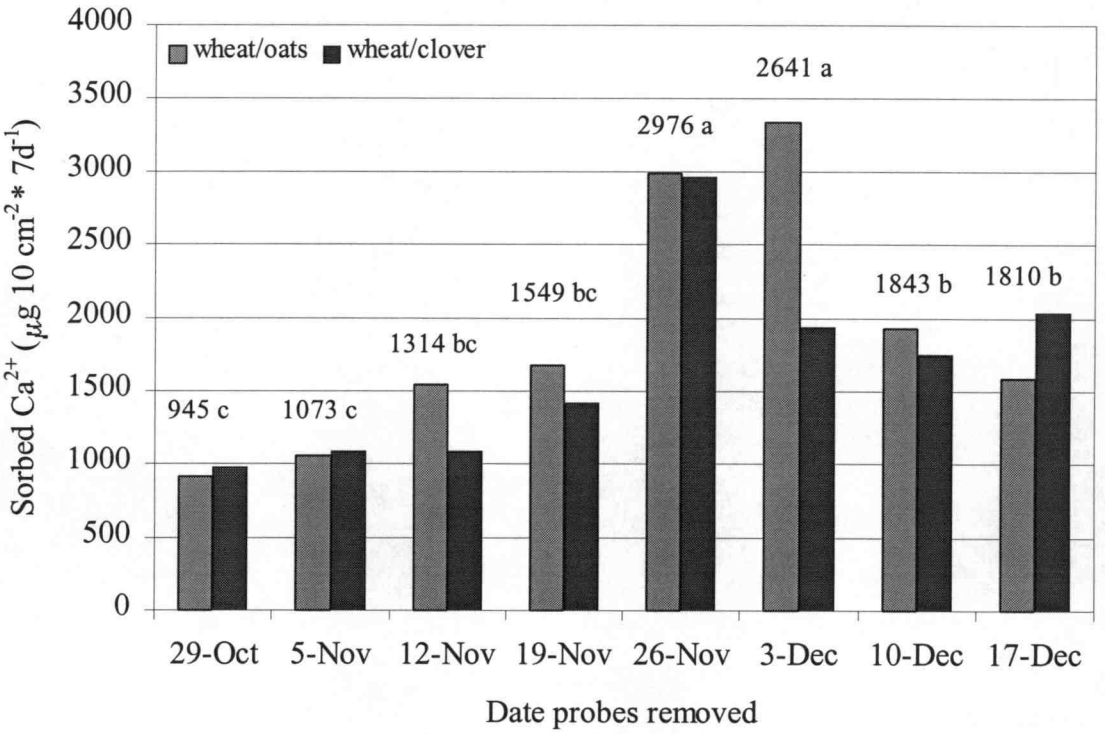

Figure 26. Calcium adsorbed by PRS probes during 7-day intervals in fall 1998.

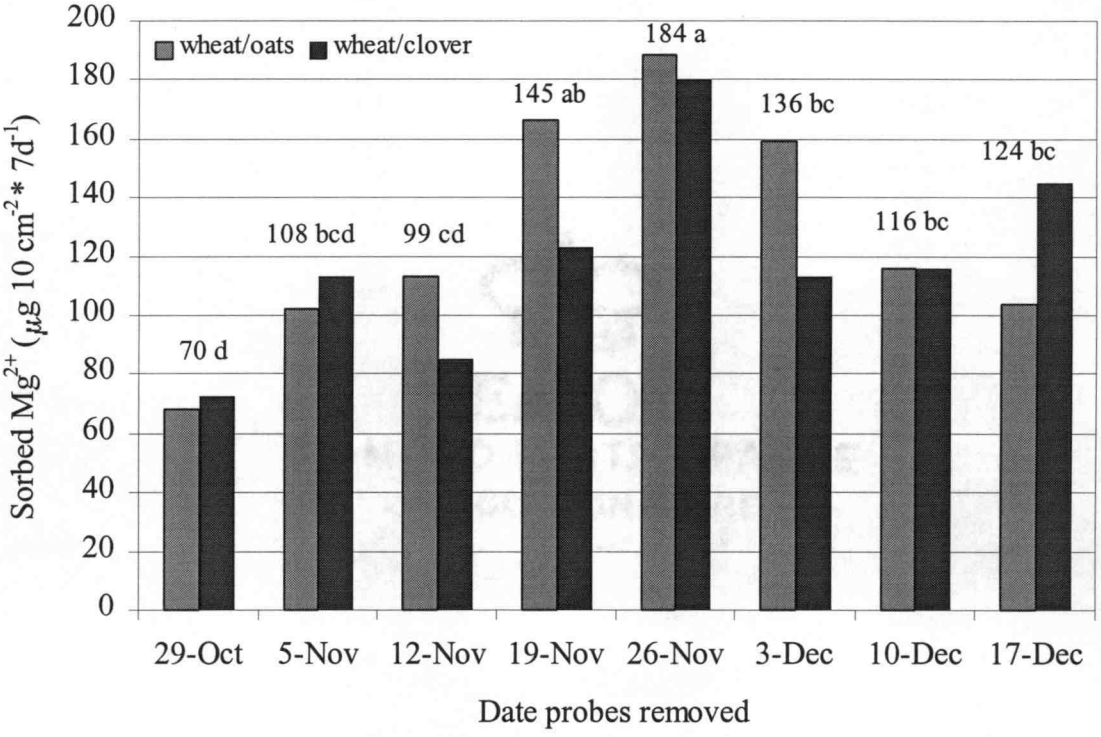

Figure 27. Magnesium adsorbed by PRS probes during 7-day intervals in fall 1998.

Table 18. Eight-week means of K, Ca, Mg, and P adsorbed by PRS probes as measured by 1-week, 4-week, and 8-week samples, and the mean plant nutrient concentrations and uptakes measured after 8 weeks.

Parameter	Sample interval ‡	Wheat-oat	Wheat-clover	Mean†
PRS K^+	1-week	177	260	219
(μg K 10 cm^{-2})	4-week	181	252	216
	8-week	181	259	220
	Mean†	180 B	257 A	
Plant K conc. (g kg^{-1})		34 B	38 A	
Plant K uptake (kg ha^{-1})		5.2 B	8.0 A	
PRS Ca^{2+}	1-week	1879	1659	1769 c
(μg Ca 10 cm^{-2})	4-week	2509	2380	2444 b
	8-week	3091	3126	3108 a
	Mean†	2493 A	2388 A	
Plant Ca conc. (g kg^{-1})		3.9 A	4.0 A	
Plant Ca uptake (kg ha^{-1})		0.62 B	0.89 A	
PRS Mg^{2+}	1-week	127	119	123 c
(μg Mg 10 cm^{-2})	4-week	157	152	155 b
	8-week	183	180	181 a
	Mean†	156 A	150 A	
Plant Mg conc. (g kg^{-1})		1.6 A	1.7 A	
Plant Mg uptake (kg ha^{-1})		0.25 B	0.36 A	

Table 18 continued. Eight week means of K, Ca, Mg, and P adsorbed by PRS probes as measured by 1-week, 4-week, and 8-week samples, and the mean plant nutrient concentrations and uptakes measured after 8 weeks.

Parameter	Sample interval ‡	Wheat-oat	Wheat-clover	Mean†
PRS PO_4^{3-}-P	1-week	51.2	42.1	46.7 c
(μg P 10 cm^{-2})	4-week	61.7	52.7	57.2 b
	8-week	72.8	63.7	68.3 a
	Mean†	61.9 A	52.8 B	
Plant P conc. (g kg^{-1})		5.4 A	5.7 A	
Plant P uptake (kg ha^{-1})		0.83 B	1.2 A	

†Means followed by different letters are significantly different at the P = 0.10 level.
‡1-week = mean of eight 1-week samples, 4 -week = mean of two 4-week samples, and 8-week = mean of one 8-week sample

were also made among the three sampling time intervals for PO_4^{3-}-P. The probes showed a significant (P = 0.10) difference in PO_4^{3-}-P between rotation in favor of the wheat following oat rotation. Plant P concentrations were not statistically different between rotations, but the uptake was significantly (P = 0.10) different due to the growth response to N. There was also a significant (P = 0.10) difference due to the sampling time of the probes. This difference was similar to the calcium and magnesium indicating that more PO_4^{3-}-P was adsorbed by the probes the longer they were installed in the soil.

PRS Probe and Soil Test Comparisons

Soil tests for three sampling dates were also analyzed for all of the previously discussed nutrients (Table 19). The soil tests did not show any significant rotation or temporal effects for NH_4^+-N. The interaction of time and rotation was significant (P = 0.05) for NO_3^--N. Means revealed that NO_3^--N was greater early in the season, and gradually decreased. This trend is very similar to the PRS probe findings.
The soil tests showed that P levels were very high (131 mg P kg^{-1}) relative to the critical level (30 kg P kg^{-1}) in the fertilizer guide for winter wheat in western Oregon. The soil tests also show a significant (P = 0.05) increase in extractable P late in the season. This is also similar to the measurements made by the PRS probes.

Statistical analysis of K from the soil tests indicate a significant (P = 0.05) rotation effect. More K was extracted from the soil where wheat followed clover as compared to oat. The soil tests showed that K levels were also very high (230 mg K kg^{-1}) relative to the critical level (100 mg K kg^{-1}) in the fertilizer guide. The PRS probes also indicated a rotation effect for K. However, the soil tests did indicate a significant (P = 0.05) time effect. According to the soil tests, the K slightly decreased over time. The

Table 19. Nutrient levels measured in the top four inches of soil in fall 1998.

Species	Date	Wheat-oat	Wheat-clover	Mean†
		-----mg kg^{-1}-----		
NH_4^+-N	22-Oct	4.7	5.7	5.2
	19-Nov	4.3	5.4	4.8
	17-Dec	4.3	4.4	4.4
	Mean	4.4	5.2	
NO_3^--N	22-Oct	7.4 b	21.0 a	14.2
	19-Nov	2.9 d	5.5 c	4.2
	17-Dec	1.5 d	1.7 d	1.6
	Mean	3.9 B	9.4 A	
P	22-Oct	124	120	122 b
	19-Nov	131	126	129 b
	17-Dec	142	144	143 a
	Mean	132	130	
K	22-Oct	230	255	242 a
	19-Nov	202	241	221 b
	17-Dec	218	236	227 b
	Mean	217 B	244 A	
		-----cmol kg^{-1}-----		
Ca	22-Oct	9.8	9.9	9.9
	19-Nov	10.0	9.9	10.0
	17-Dec	9.4	10.7	10.0
	Mean	9.7	10.2	
Mg	22-Oct	0.7	0.7	0.7
	19-Nov	0.7	0.7	0.7
	17-Dec	0.7	0.7	0.7
	Mean	0.7	0.7	
		pH		
pH	22-Oct	6.1	6.1	6.1 b
	19-Nov	6.2	6.2	6.2 a
	17-Dec	6.1	6.3	6.2 a
	Mean	6.2	6.2	

†Means followed by different letters are significantly different at the P = 0.05 level.

probes did not detect this change.

The soil tests for calcium and magnesium did not indicate any significant differences between rotations, which is exactly what the probes recorded. Lastly, the pH of the soil was well above where any major limitations might occur. However, standard soil tests did point out a significant ($P = 0.05$) time effect. The pH slightly decreased over time, but the decrease was minimal.

The trends observed by the standard soil tests were very similar to those observed by the PRS probes. The significant rotation effects indicated by the soil tests for NO_3^--N and K were similar to the probes. However, the relative difference between the rotations was greater for the probes. Additionally, the probes showed a significant rotation difference for PO_4^{3-}-P, whereas the soil test did not. These differences point out the increased sensitivity of the probes to detect these differences.

While beyond the scope of this study, it is possible that the difference in sampling time for the amount of calcium and magnesium adsorbed by the probes could be due to differences in cation affinity between the soil and the probe. The probes are likely a stronger sink for ions than the soil. Thus, equilibrium between the probe and the soil needs to be achieved. The soil would be expected to have a higher affinity for the divalent cations than for the monovalent cations. Therefore, the soil and probe would be expected to reach equilibrium with potassium before reaching equilibrium with calcium and magnesium. This could be why there was no significant difference in the three sampling times for K, but there was for both calcium and magnesium.

The significant increase of P in the soil late in the season could be related to the reduction of iron. In acidic soils phosphorus exists, in part, as iron phosphates. As the

soil approaches saturation and anaerobic conditions arise, the iron begins to be reduced from Fe^{3+} to Fe^{2+}, and the soil solution concentrations of P increase. This hypothesis is beyond the scope of this research, but could possibly explain the slight increase measured in the soil later in the season. This slight increase could have also been due to an insufficient number of sampling times.

PRS Probe Diffusion Analysis

Since the PRS probe is solely a diffusion-based instrument, it was of interest to study the influence of soil temperature and volumetric water content on the diffusion of nutrients to the probe. Measurements were made so that a relative effective diffusion coefficient for K could be calculated. Daily precipitation data and weekly volumetric water content and soil temperature were recorded. The substantial rainfall began to occur between November 19 and November 26 (Figure 24). Coincidentally, the volumetric water content of the soil increased substantially. This increase would have altered the diffusion of nutrient ions in the soil, and consequently affected the amount adsorbed by the PRS probes. Relative effective diffusion coefficients were calculated for K^+ using the following equations.

$$D_l = k_b T / 6\pi r_i \eta \qquad [1]$$

$$D_e = D_l \theta f_l dC_l / dC_s \qquad [2]$$

The K^+ means were plotted again after correcting for changes in soil temperature and volumetric water content (Figure 26). Minimal differences were observed in the responses between the adjusted and the unadjusted K levels adsorbed by the probes. The analysis of variance for the unadjusted K levels showed a mean square for error of 45.3 while the mean square for error for the adjusted K levels was 46.5 (Table 20). Therefore,

the variability of the measurements essentially does not increase or decrease by factoring out the soil temperature and volumetric water content. However, the decrease in the probability of the interaction term from 0.27 to 0.19 suggested that factoring out the variability of the soil temperature and volumetric water content increased the precision of the estimates.

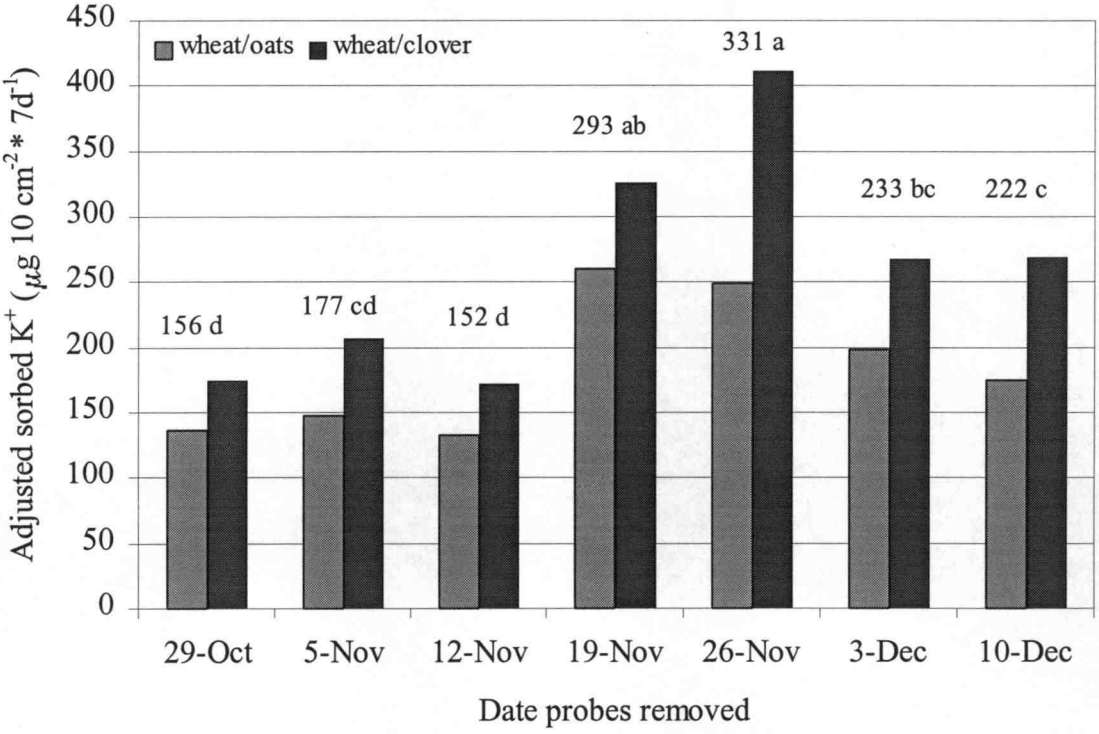

Figure 28. Potassium adsorbed by PRS probes during 7-day intervals after adjustment for temporal changes in soil temperature and volumetric water content.

Table 20. Analysis on variance for potassium adsorbed by PRS probes in fall 1998 (October 29 through December 10).

		Unadjusted data			Adjusted data		
Source	d.f.	Mean Sq.	F-Value	Prob.	Mean Sq.	F-Value	Prob.
Replication	3	84.5	1.19		99.9	1.38	0.2804
Time	6	436.4	6.15	0.0012	769.8	10.65	0.0000
Error	18	70.9			72.3		
Rotation	1	1531.0	33.80	0.0000	1630.8	35.07	0.0000
Time x Rotation	6	62.5	1.38	0.2684	74.9	1.61	0.1934
Error	21	45.3			46.5		
Total	55						

CONCLUSIONS

Crop Responses to Treatments

Crop rotation and N fertilizer rate influenced grain yield, grain protein, total biomass, and N uptake of winter wheat. The yield was consistently greater for wheat following clover for each of the three growing seasons and for the three-year average. The maximum yield was achieved at N fertilizer rates between 100 and 200 kg N ha^{-1}. The mean grain protein was also greater for the wheat after clover rotation for each growing season, and for the three-year average. Likewise, the N uptake was greater for the wheat after clover rotation. There was a near parallel relationship for N uptake between the rotations. Nitrogen uptake measured in the 0 kg N ha^{-1} plots were 15 to 37 kg N ha^{-1} greater for the wheat following clover rotation than for wheat following oat. Therefore, the clover is supplying more available N than the oats to the wheat. Fertilizer equivalent values derived from the N uptake data resulted in a three-year average of 44.5 kg N ha^{-1}. This is the amount of fertilizer required by the wheat after oat rotation to equal the N status of the wheat following clover. A three-year average fertilizer equivalent value was also calculated using the yield data. This average value was 49.0 kg N ha^{-1}. The similarity of these estimates and the independence of the two calculations suggest that the rotation effect was primarily caused by differences in nitrogen availability.

Plant, Soil, and PRS Probe Responses

Standard soil tests in the spring did not reveal a rotation effect for either NH_4^+-N or NO_3^--N. These two forms of N remained at relatively low concentrations throughout the sample period. The PRS probes did not detect rotational differences in plant available

N either. However, the probes detected a temporal effect in NH_4^+-N. This was most likely a reflection of the precipitation increasing the diffusion of the NH_4^+-N to the probe. The spring study also lead to the conclusion that there was no difference between the one-week sampling time and the two-week sampling time.

In the fall, the PRS probes installed for seven days detected a significant rotation difference in inorganic N. The wheat following clover rotation had higher levels of both NH_4^+-N and NO_3^--N. Relative comparisons of one-week probe means and plant N uptake indicated that the probes were capable of estimating the amount of plant available N extremely well. It was concluded that the one-week sampling interval provided the best estimate of N uptake by the crop.

The PRS probes installed for seven days also detected rotational differences in K and PO_4^{3-}-P. The K was greater in the wheat following clover, but the PO_4^{3-}-P was greater in the wheat after oat. Temporal effects were also detected for these two nutrients and for calcium and magnesium. Differences in K due to sampling time interval were not observed. However, there were significant differences in PO_4^{3-}-P, calcium, and magnesium due to the sampling time interval. In all cases, the 8-week sampling time resulted in greater recovery of all nutrients measured by the PRS probes. The probe data agreed with trends observed by the plant tissue concentration and the standard soil tests. However, the probes were able to detect greater relative differences between rotations. Therefore, the probes are more sensitive and capable of pointing out these nutritional differences.

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APPENDIX

Appendix table 1. Agronomic data from Hyslop Farm small plot research site for 1995-96 growing season.

			6-m sample				Whole plot		
			Straw		Grain		Yield	TW	Protein
Block	Treatment	Rotation	Kg/ha	N%	Kg/ha	N%	Kg/ha	(g/qt)	(%)
1	1	1	2591	0.29	1845	1.43	2231	873	8.43
2	1	1	4198	0.25	3067	1.51	2375	866	8.58
3	1	1	2460	0.23	2075	1.47	2464	871	8.61
4	1	1	3772	0.29	2632	1.57	2119	865	8.13
1	1	2	4986	0.26	2870	1.53	3984	868	8.45
2	1	2	2895	0.28	2132	1.53	3034	853	8.64
3	1	2	5855	0.26	4535	1.56	4790	872	8.46
4	1	2	2394	0.23	2895	1.68	2978	872	8.86
1	2	1	5437	0.25	3756	1.31	4427	856	8.12
2	2	1	5453	0.21	3985	1.24	3375	850	7.36
3	2	1	7470	0.22	4822	1.28	3741	836	7.76
4	2	1	2435	0.23	3813	1.27	3830	841	7.17
1	2	2	8905	0.22	6527	1.57	4666	855	8.30
2	2	2	9610	0.25	6084	1.51	5361	859	8.51
3	2	2	9553	0.23	6880	1.40	5876	861	7.94
4	2	2	9602	0.24	6642	1.56	5537	858	8.36
1	3	1	10562	0.25	7175	1.40	5872	850	7.98
2	3	1	8856	0.19	6199	1.28	5853	845	7.71
3	3	1	8446	0.24	5929	1.33	6004	857	7.90
4	3	1	9414	0.21	6765	1.40	5439	844	7.20
1	3	2	11160	0.30	8725	1.56	6560	867	8.56
2	3	2	10381	0.27	7708	1.63	6613	862	8.49
3	3	2	7191	0.28	5314	1.50	6723	866	8.12
4	3	2	7528	0.29	5912	1.46	7823	857	8.39
1	4	1	10545	0.35	7273	1.32	7000	858	8.03
2	4	1	11882	0.34	9299	1.44	7449	853	7.91
3	4	1	5166	0.25	4100	1.42	7703	853	7.84
4	4	1	10365	0.29	8307	1.42	6272	855	7.62
1	4	2	10652	0.35	5396	1.54	7114	862	8.17
2	4	2	8971	0.26	7060	1.43	6844	870	8.23
3	4	2	11037	0.25	6732	1.47	7762	864	8.10
4	4	2	11431	0.27	9135	1.54	7176	872	8.34
1	5	1	11136	0.43	8208	1.48	7639	865	8.37
2	5	1	9471	0.33	7396	1.47	7821	865	8.25
3	5	1	10758	0.38	7970	1.54	8255	847	8.47
4	5	1	15252	0.33	8774	1.30	8094	868	8.41
1	5	2	11603	0.53	8102	1.83	9043	870	8.91
2	5	2	9766	0.50	9733	1.75	8748	858	9.07
3	5	2	16064	0.41	12439	1.57	8038	872	8.44
4	5	2	11373	0.36	8823	1.49	8343	859	8.25

Rotation: 1 = Wheat-oat 2 = Wheat-clover

Treatment: 1 = 0 kg ha^{-1} 2 = 50 kg ha^{-1} 3 = 100 kg ha^{-1}
4 = 150 kg ha^{-1} 5 = 200 kg ha^{-1}

Appendix table 2. Agronomic data from Hyslop Farm small plot research site for 1996-97 growing season.

			6-m sample				Whole plot		
			Straw		Grain		Yield	TW	Protein
Block	Treatment	Rotation	Kg/ha	N%	Kg/ha	N%	Kg/ha	(g/qt)	(%)
1	1	1	1673	0.20	1083	1.14	1288	840	7.5
2	1	1	1624	0.35	1058	1.34	1043	836	7.9
3	1	1	1591	0.26	1468	1.25	1024	834	7.7
4	1	1	1886	0.23	1476	1.27	1190	837	7.8
1	1	2	5807	0.17	3781	1.22	2839	831	7.9
2	1	2	6324	0.15	4101	1.26	3756	842	8.2
3	1	2	5643	0.17	4101	1.31	3218	841	8.3
4	1	2	4995	0.18	2928	1.40	3815	836	8.3
1	2	1	6389	0.13	4158	1.09	3022	827	6.7
2	2	1	5495	0.15	3617	1.15	2833	820	7.2
3	2	1	4446	0.16	3150	1.10	2594	825	6.8
4	2	1	7603	0.12	5331	1.20	3025	824	7.2
1	2	2	9129	0.15	5307	1.19	4967	838	7.7
2	2	2	14985	0.16	6972	1.25	5517	837	7.9
3	2	2	11713	0.15	6767	1.30	5889	841	7.9
4	2	2	7644	0.22	4388	1.50	4851	846	8.4
1	3	1	12680	0.14	8514	1.16	4909	839	7.2
2	3	1	8604	0.17	6357	1.17	4464	837	7.2
3	3	1	10187	0.19	6660	1.26	4596	831	7.1
4	3	1	9662	0.17	6316	1.28	5398	833	7.1
1	3	2	12352	0.23	7882	1.38	6312	849	8.0
2	3	2	11376	0.29	8317	1.33	6849	852	8.2
3	3	2	14321	0.25	9719	1.37	7061	856	8.2
4	3	2	11901	0.22	7390	1.48	6179	860	8.5
1	4	1	9613	0.23	8432	1.31	5194	843	8.1
2	4	1	10696	0.32	8801	1.63	6188	847	8.1
3	4	1	11393	0.13	7767	1.29	6261	839	7.4
4	4	1	9408	0.14	8374	1.46	6675	846	7.8
1	4	2	13739	0.30	9621	1.55	7712	865	8.6
2	4	2	13607	0.26	9137	1.48	7997	859	8.4
3	4	2	12156	0.35	7439	1.51	7984	858	8.9
4	4	2	12680	0.32	8727	1.59	7780	869	9.2
1	5	1	11138	0.36	8612	1.46	6961	850	8.1
2	5	1	11762	0.33	7833	1.80	7209	871	9.3
3	5	1	8661	0.36	7308	1.50	7305	849	8.3
4	5	1	12680	0.31	10105	1.72	8070	862	8.7
1	5	2	13148	0.46	10220	1.77	7140	865	9.5
2	5	2	13181	0.44	10622	1.73	7843	870	9.4
3	5	2	12393	0.39	8801	1.71	7689	864	9.8
4	5	2	10843	0.52	6709	1.87	6998	857	10.1

Rotation: 1 = Wheat-oat 2 = Wheat-clover

Treatment: 1 = 0 kg ha^{-1} 2 = 50 kg ha^{-1} 3 = 100 kg ha^{-1} 4 = 150 kg ha^{-1} 5 = 200 kg ha^{-1}

Appendix table 3. Agronomic data from Hyslop Farm small plot research site for 1997-98 growing season.

			3-m sample				Whole plot		
			Straw		Grain		Yield	TW	Protein
Block	Treatment	Rotation	Kg/ha	N%	Kg/ha	N%	Kg/ha	(g/qt)	(%)
1	1	1	4014	0.31	2799	1.40	2460	840	7.62
2	1	1	3201	0.30	2221	1.47	1962	851	7.98
3	1	1	3385	0.30	2147	1.46	2074	843	7.77
4	1	1	2366	0.32	2174	1.47	1450	846	7.93
1	1	2	6117	0.26	4244	1.46	3749	845	7.97
2	1	2	5445	0.25	4236	1.35	3337	848	7.92
3	1	2	5812	0.28	4588	1.48	3562	845	7.69
4	1	2	5852	0.27	3593	1.46	3586	842	7.64
1	2	1	6825	0.22	4677	1.29	3957	833	7.27
2	2	1	8258	0.26	5582	1.30	4788	841	7.54
3	2	1	5611	0.25	5207	1.31	3253	826	6.90
4	2	1	7298	0.23	4657	1.31	4231	821	7.10
1	2	2	8730	0.27	5330	1.41	5062	835	7.91
2	2	2	8593	0.32	6222	1.44	4982	831	8.05
3	2	2	8124	0.34	5832	1.53	4710	836.2	7.71
4	2	2	8652	0.30	5682	1.44	5016	830	7.52
1	3	1	12442	0.33	6506	1.37	7029	832	7.37
2	3	1	8917	0.28	7475	1.40	5038	831	7.43
3	3	1	9291	0.29	5988	1.33	5249	832	7.42
4	3	1	9869	0.30	6242	1.46	5576	828	7.75
1	3	2	9407	0.38	6142	1.63	5314	816	9.11
2	3	2	9852	0.45	7215	1.74	5566	826	9.19
3	3	2	9091	0.50	5059	1.65	5136	815	8.99
4	3	2	10165	0.49	5878	1.77	5743	812	9.21
1	4	1	10724	0.40	7808	1.68	5749	827	8.25
2	4	1	11501	0.47	6421	1.72	6166	820	8.85
3	4	1	11588	0.33	7766	1.57	6212	842	8.10
4	4	1	11184	0.43	6115	1.79	5995	832	8.90
1	4	2	10801	0.43	7311	1.94	5790	815	9.61
2	4	2	10861	0.45	7174	1.85	5822	824	9.40
3	4	2	9982	0.48	6161	1.99	5351	805	10.07
4	4	2	10296	0.59	5633	2.02	5520	780	9.97
1	5	1	10878	0.55	6665	1.76	5049	799	9.58
2	5	1	14108	0.43	7338	1.86	6548	818	9.55
3	5	1	13814	0.49	7497	1.97	6412	824	9.23
4	5	1	14435	0.59	7108	2.08	6700	816	9.49
1	5	2	11995	0.78	4762	2.68	5567	772	11.45
2	5	2	10656	0.76	4724	2.64	4946	738	11.82
3	5	2	11084	0.62	5756	2.42	5144	756	11.70
4	5	2	12414	0.79	5530	2.34	5762	805	10.65

Rotation: 1 = Wheat-oat 2 = Wheat-clover

Treatment: 1 = 0 kg ha^{-1} 2 = 50 kg ha^{-1} 3 = 100 kg ha^{-1}
4 = 150 kg ha^{-1} 5 = 200 kg ha^{-1}

Appendix table 4. PRS probe measurements at Hyslop Farm in spring 1998.

Date	Block	Rotation	Probe	NH_4^+-N	NO_3^--N
				--μg 10 cm^{-2} 14 d^{-1}--	
1	1	1	1	12.1	1.5
1	1	1	2	11.6	1.6
1	1	1	3	3.1	4.0
1	1	2	1	10.7	0.0
1	1	2	2	10.5	3.4
1	1	2	3	5.0	3.2
1	2	1	1	10.2	30.1
1	2	1	2	19.2	6.8
1	2	1	3	1.6	8.4
1	2	2	1	18.6	14.2
1	2	2	2	14.1	15.3
1	2	2	3	13.8	9.3
1	3	1	1	9.3	110.0
1	3	1	2	4.1	99.7
1	3	1	3	6.9	11.0
1	3	2	1	3.3	5.1
1	3	2	2	1.7	1.6
1	3	2	3	7.6	1.9
1	4	1	1	4.0	1.6
1	4	1	2	9.9	1.1
1	4	1	3	5.7	4.4
1	4	2	1	5.5	5.5
1	4	2	2	6.3	10.7
1	4	2	3	3.7	7.5
2	1	1	1	11.4	64.4
2	1	1	2	8.6	5.1
2	1	1	3	18.1	3.4
2	1	2	1	9.2	6.6
2	1	2	2	29.6	12.9
2	1	2	3	8.4	9.3
2	2	1	1	4.0	10.5
2	2	1	2	14.6	9.7
2	2	1	3	3.5	20.2
2	2	2	1	8.3	15.8
2	2	2	2	6.9	10.1
2	2	2	3	4.3	13.6

Appendix table 4 continued. PRS probe measurements at Hyslop Farm in spring 1998.

Date	Block	Rotation	Probe	NH_4^+-N	NO_3^--N
				--μg 10 cm^{-2} 14 d^{-1}--	
2	3	1	1	3.9	8.3
2	3	1	2	15.5	30.2
2	3	1	3	20.1	10.6
2	3	2	1	5.8	2.5
2	3	2	2	2.9	4.9
2	3	2	3	3.2	5.4
2	4	1	1	4.9	7.2
2	4	1	2	7.0	10.1
2	4	1	3	2.4	3.0
2	4	2	1	15.0	12.5
2	4	2	2	8.8	8.9
2	4	2	3	14.4	20.3
3	1	1	1	6.7	20.1
3	1	1	2	5.6	11.2
3	1	1	3	31.3	23.5
3	1	2	1	22.3	6.7
3	1	2	2	15.6	10.1
3	1	2	3	17.9	5.6
3	2	1	1	19.0	17.9
3	2	1	2	4.5	22.3
3	2	1	3	49.2	23.5
3	2	2	1	4.5	24.6
3	2	2	2	3.4	19.0
3	2	2	3	22.3	10.1
3	3	1	1	6.7	15.6
3	3	1	2	14.5	15.6
3	3	1	3	32.4	11.2
3	3	2	1	6.7	13.4
3	3	2	2	4.5	11.2
3	3	2	3	12.3	14.5
3	4	1	1	13.4	12.3
3	4	1	2	31.3	6.7
3	4	1	3	39.1	4.5

Appendix table 4 continued. PRS probe measurements at Hyslop Farm in spring 1998.

Date	Block	Rotation	Probe	NH_4^+-N	NO_3^--N
				--μg 10 cm^{-2} 14 d^{-1}--	
3	4	2	1	5.6	8.9
3	4	2	2	19.0	13.4
3	4	2	3	30.2	6.7
4	1	1	1	10.1	21.2
4	1	1	2	2.2	7.8
4	1	1	3	32.4	10.1
4	1	2	1	3.4	25.7
4	1	2	2	17.9	41.3
4	1	2	3	44.7	10.1
4	2	1	1	4.5	14.5
4	2	1	2	12.3	4.5
4	2	1	3	13.4	30.2
4	2	2	1	25.7	7.8
4	2	2	2	16.8	5.6
4	2	2	3	91.6	10.1
4	3	1	1	61.5	14.5
4	3	1	2	13.4	16.8
4	3	1	3	7.8	12.3
4	3	2	1	5.6	29.1
4	3	2	2	10.1	20.1
4	3	2	3	3.4	25.7
4	4	1	1	4.5	8.9
4	4	1	2	13.4	5.6
4	4	1	3	7.8	14.5
4	4	2	1	11.2	16.8
4	4	2	2	10.1	6.7
4	4	2	3	25.7	7.8
5	1	1	1	3.4	2.2
5	1	1	2	11.2	20.1
5	1	1	3	2.2	5.6
5	1	2	1	3.4	7.8
5	1	2	2	4.5	<1.1
5	1	2	3	1.1	10.1
5	2	1	1	6.7	8.9
5	2	1	2	2.2	1.1
5	2	1	3	3.4	4.5

Appendix table 4 continued. PRS probe measurements at Hyslop Farm in spring 1998.

Date	Block	Rotation	Probe	NH_4^+-N	NO_3^--N
				--μg 10 cm^{-2} 14 d^{-1}--	
5	2	2	1	10.1	7.8
5	2	2	2	4.5	<1.1
5	2	2	3	6.7	<1.1
5	3	1	1	3.4	<1.1
5	3	1	2	1.1	2.2
5	3	1	3	2.2	6.7
5	3	2	1	6.7	2.2
5	3	2	2	6.7	16.8
5	3	2	3	3.4	6.7
5	4	1	1	3.4	7.8
5	4	1	2	4.5	17.9
5	4	1	3	5.6	8.9
5	4	2	1	5.6	17.9
5	4	2	2	2.2	5.6
5	4	2	3	7.8	2.2
6	1	1	1	4.5	29.1
6	1	1	2	7.8	12.3
6	1	1	3	6.7	10.1
6	1	2	1	7.8	54.7
6	1	2	2	10.1	29.1
6	1	2	3	4.5	48.0
6	2	1	1	4.5	13.4
6	2	1	2	4.5	11.2
6	2	1	3	2.2	16.8
6	2	2	1	2.2	11.2
6	2	2	2	4.5	14.5
6	2	2	3	13.4	21.2
6	3	1	1	2.2	8.9
6	3	1	2	2.2	30.2
6	3	1	3	2.2	16.8
6	3	2	1	2.2	20.1
6	3	2	2	2.2	24.6
6	3	2	3	2.2	32.4

Appendix table 4 continued. PRS probe measurements at Hyslop Farm in spring 1998.

Date	Block	Rotation	Probe	NH_4^+-N	NO_3^--N
				--μg 10 cm^{-2} 14 d^{-1}--	
6	4	1	1	1.1	26.8
6	4	1	2	2.2	24.6
6	4	1	3	1.1	21.2
6	4	2	1	8.9	61.5
6	4	2	2	2.2	29.1
6	4	2	3	6.7	24.6

Date: 1 = 3/19/98† 2 = 3/26/98 3 = 4/2/98 4 = 4/16/98 5 = 4/30/98
6 = 5/14/98

Rotation: 1 = Wheat-oat 2 = Wheat-clover

†Probes were removed after a 7 day interval.

Appendix table 5. Measurements and tissue analysis of 30 cm of row wheat samples in spring 1998.

Block	Date	Rotation	DMY†	%N	%C
			--kg ha^{-1}--		
1	1	1	698.4	3.76	42.6
2	1	1	595.1	3.38	39.7
3	1	1	605.2	2.79	40.8
4	1	1	716.2	3.31	39.5
1	1	2	1824.0	3.65	39.4
2	1	2	1285.9	3.16	38.7
3	1	2	1321.3	4.33	41.5
4	1	2	1433.9	4.02	43.0
1	2	1	623.4	2.52	44.4
2	2	1	672.6	2.23	44.0
3	2	1	1049.9	2.52	43.9
4	2	1	803.8	2.29	43.8
1	2	2	2903.5	2.09	43.4
2	2	2	1295.9	2.31	43.7
3	2	2	1525.6	2.21	43.6
4	2	2	524.9	2.17	43.9
1	3	1	820.2	2.03	45.2
2	3	1	1558.4	1.82	45.5
3	3	1	820.2	2.00	45.5
4	3	1	1197.5	2.00	45.2
1	3	2	2887.1	1.74	45.5
2	3	2	1706.0	1.92	45.3
3	3	2	2493.4	1.94	45.5
4	3	2	2214.6	1.75	45.2
1	4	1	1853.7	1.70	44.0
2	4	1	1509.2	1.44	44.2
3	4	1	1099.1	1.75	44.1
4	4	1	2509.8	1.31	44.0
1	4	2	3166.0	1.22	46.1
2	4	2	3116.8	1.18	44.1
3	4	2	2837.9	1.52	44.4
4	4	2	2805.1	1.31	44.2

Appendix table 5 continued. Measurements and tissue analysis of 30 cm of row wheat samples in spring 1998.

Block	Date	Rotation	DMY†	%N	%C
			--kg ha^{-1}--		
1	5	1	2214.6	1.29	43.9
2	5	1	1263.1	1.29	44.0
3	5	1	1574.8	1.08	44.1
4	5	1	1509.2	1.12	43.9
1	5	2	6266.4	0.87	44.1
2	5	2	3838.6	0.95	44.3
3	5	2	3559.7	1.21	44.4
4	5	2	3789.4	1.06	44.0
1	6	1	2345.8	1.00	44.0
2	6	1	4642.4	0.96	44.0
3	6	1	3149.6	1.07	44.1
4	6	1	3592.5	0.89	44.2
1	6	2	9186.4	0.81	44.8
2	6	2	3822.2	0.76	44.4
3	6	2	7874.0	0.92	44.6
4	6	2	10941.6	0.83	44.2

†Dry Matter Yield

Date: 1 = 2/18/98 2 = 3/26/98 3 = 4/2/98 4 = 4/16/98 5 = 4/30/98 6 = 5/14/98

Rotation: 1 = Wheat-oat 2 = Wheat-clover

Appendix table 6. Soil test measurements from Hyslop long term rotation plots in spring 1998.

Block	Date	Rotation	NH_4^+-N	NO_3^--N
			---mg kg^{-1}---	
1	1	1	5.7	1.2
2	1	1	4.1	0.9
3	1	1	11.0	2.2
4	1	1	5.0	0.9
1	1	2	10.6	1.8
2	1	2	4.2	1.1
3	1	2	5.4	1.1
4	1	2	4.8	1.3
1	2	1	3.0	0.8
2	2	1	2.9	0.8
3	2	1	3.2	0.9
4	2	1	4.5	0.9
1	2	2	3.5	0.9
2	2	2	3.2	0.8
3	2	2	3.4	0.8
4	2	2	4.1	0.9
1	3	1	4.6	0.8
2	3	1	4.6	0.8
3	3	1	4.7	0.9
4	3	1	4.6	0.8
1	3	2	4.6	1.1
2	3	2	4.1	0.9
3	3	2	4.0	0.9
4	3	2	4.6	0.9
1	4	1	3.7	0.7
2	4	1	3.7	0.7
3	4	1	4.1	0.8
4	4	1	4.5	0.8
1	4	2	3.6	0.9
2	4	2	3.5	0.7
3	4	2	4.4	0.8
4	4	2	4.3	0.8

Appendix table 6 continued. Soil test measurements from Hyslop long term rotation plots in spring 1998.

Block	Date	Rotation	NH_4^+-N	NO_3^--N
			---mg kg^{-1}---	
1	5	1	4.0	0.6
2	5	1	2.9	0.8
3	5	1	4.3	0.7
4	5	1	3.7	0.8
1	5	2	3.9	0.7
2	5	2	3.1	0.8
3	5	2	3.1	0.8
4	5	2	3.9	0.7
1	6	1	3.8	<1.5
2	6	1	2.8	<1.5
3	6	1	3.2	<1.5
4	6	1	4.3	<1.5
1	6	2	4.4	<1.5
2	6	2	3.3	<1.5
3	6	2	3.1	<1.5
4	6	2	4.1	<1.5

Date: 1 = 3/12/98 2 = 3/26/98 3 = 4/2/98 4 = 4/16/98
5 = 4/30/98 6 = 5/14/98
Rotation: 1 = Wheat-oat 2 = Wheat-clover

Appendix 7. PRS probe ion exchange capacity measurements.

Probe	Treatment	Trial 1		Trial 2
		NH_4^+-N	NO_3^--N	NH_4^+-N
		--μg 10 cm^{-2}--		μg 10 cm^{-2}
-	1	741.9	745.2	694.8
1	2	2256	361	2088
2	2	2197	425	2232
3	2	2345	408	2045
4	2	2190	448	2131
5	2	2094	409	2162
6	2	1897	453	2267
7	2	2036	420	2400
8	2	2115	397	2342
9	2	2091	403	2091
10	2	1979	413	2095
11	3	2556	413	-
12	3	2501	370	-

Treatment: 1 = stock solution† 2 = 10 probes/500 ml 3 = 2 probes/500 ml

†Stock solution concentrations are recorded in mg L^{-1}.

Appendix table 8. PRS probe measurements at Hyslop Farm in fall 1998.

Date	Block	Rotation	Treatment	NH_4^+-N	NO_3^--N	K^+	PO_4^{3-}-P	Ca^{2+}	Mg^{2+}
				----------μg 10 cm^{-2}----------					
1	1	1	1	12.12	174.28	125.50	23.46	429.05	51.49
1	1	2	1	14.78	263.44	198.70	22.12	589.94	45.05
1	2	1	1	9.67	59.99	198.70	23.46	1555.31	93.32
1	2	2	1	7.18	386.09	167.33	17.43	1501.68	102.97
1	3	1	1	6.04	256.07	104.58	25.47	911.73	70.79
1	3	2	1	10.48	396.99	177.79	23.46	1018.99	77.23
1	4	1	1	4.86	143.42	115.04	19.44	750.84	57.92
1	4	2	1	9.67	321.33	156.87	20.78	804.47	64.36
2	1	1	1	11.91	177.50	146.41	36.87	1287.15	99.75
2	1	2	1	11.55	141.54	94.12	16.76	536.31	45.05
2	2	1	1	18.28	138.43	209.16	28.83	589.94	64.36
2	2	2	1	9.07	475.47	230.08	28.16	1126.26	128.72
2	3	1	1	7.95	367.90	167.33	58.32	1501.68	151.24
2	3	2	1	11.11	773.66	303.28	48.27	1716.20	148.02
2	4	1	1	8.86	234.15	135.96	58.32	858.10	93.32
2	4	2	1	11.82	334.44	292.83	46.26	965.36	131.93
3	1	1	1	8.12	251.59	177.79	48.27	1662.57	135.15
3	1	2	1	8.16	397.74	240.54	38.88	1608.94	109.41
3	2	1	1	4.30	130.81	94.12	31.51	697.21	51.49
3	2	2	1	6.21	296.41	146.41	22.12	804.47	67.58

Appendix table 8 continued. PRS probe measurements at Hyslop Farm in fall 1998.

Date	Block	Rotation	Treatment	NH_4^+-N	NO_3^--N	K^+	PO_4^{3-}-P	Ca^{2+}	Mg^{2+}
				----------μg 10 cm^{-2}----------					
3	3	1	1	5.18	314.43	146.41	39.55	2735.20	180.20
3	3	2	1	4.71	288.27	146.41	37.54	1126.26	93.32
3	4	1	1	4.83	129.76	156.87	32.85	1072.63	86.88
3	4	2	1	5.07	111.75	209.16	21.45	804.47	70.79
4	1	1	1	7.92	151.54	177.79	60.34	1340.78	138.37
4	1	2	1	16.07	162.72	271.91	22.79	1716.20	131.93
4	2	1	1	5.51	120.11	282.37	56.98	2413.41	241.34
4	2	2	1	8.44	321.62	292.83	50.28	1608.94	154.46
4	3	1	1	6.59	313.74	167.33	63.69	1287.15	148.02
4	3	2	1	7.72	139.88	219.62	44.25	1179.89	102.97
4	4	1	1	6.42	115.26	240.54	69.72	1662.57	138.37
4	4	2	1	5.12	255.32	303.28	36.87	1179.89	102.97
4	1	1	2	14.47	473.80	209.16	94.53	3539.66	225.25
4	1	2	2	15.67	704.65	261.45	47.60	2788.83	193.07
4	2	1	2	4.92	414.82	230.08	76.42	4236.87	241.34
4	2	2	2	11.06	948.95	386.95	61.68	4612.29	337.88
4	3	1	2	10.94	708.34	198.70	101.23	4612.29	289.61
4	3	2	2	6.39	748.92	188.25	77.09	4719.55	241.34
4	4	1	2	9.71	435.24	261.45	85.14	3378.77	234.91
4	4	2	2	14.11	646.94	345.12	75.08	4612.29	289.61

Appendix table 8 continued. PRS probe measurements at Hyslop Farm in fall 1998.

Date	Block	Rotation	Treatment	NH_4^+-N	NO_3^--N	K^+	PO_4^{3-}-P	Ca^{2+}	Mg^{2+}
				----------μg 10 cm^{-2}----------					
5	1	1	1	10.56	106.12	188.25	71.73	2949.72	176.98
5	1	2	1	13.06	94.40	449.70	61.01	3164.25	173.77
5	2	1	1	7.95	81.69	271.91	48.27	3325.14	212.38
5	2	2	1	12.88	207.06	449.70	56.31	3003.35	202.73
5	3	1	1	7.22	65.02	209.16	68.38	2788.83	189.85
5	3	2	1	7.76	75.59	345.12	59.66	3486.03	199.51
5	4	1	1	8.52	30.50	261.45	52.96	2896.09	173.77
5	4	2	1	9.07	81.22	292.83	70.39	2198.88	144.80
6	1	1	1	9.99	53.34	230.08	58.99	2520.67	154.46
6	1	2	1	7.42	59.33	282.37	30.17	2467.04	141.59
6	2	1	1	5.12	44.04	188.25	43.58	1769.83	99.75
6	2	2	1	5.86	127.21	167.33	37.54	1501.68	80.45
6	3	1	1	7.40	50.24	156.87	43.58	6650.28	250.99
6	3	2	1	9.48	65.60	209.16	71.06	1716.20	96.54
6	4	1	1	7.10	53.34	167.33	57.65	2413.41	131.93
6	4	2	1	12.96	60.63	345.12	63.69	2091.62	135.15
7	1	1	1	7.15	93.15	146.41	61.01	1340.78	86.88
7	1	2	1	8.16	81.05	209.16	38.21	1877.09	109.41
7	2	1	1	7.04	65.89	198.70	58.32	2306.15	141.59
7	2	2	1	6.37	171.65	313.74	42.23	1340.78	93.32

Appendix table 8 continued. PRS probe measurements at Hyslop Farm in fall 1998.

Date	Block	Rotation	Treatment	NH_4^+-N	NO_3^--N	K^+	PO_4^{3-}-P	Ca^{2+}	Mg^{2+}
				----------μg 10 cm^{-2}----------					
7	3	1	1	5.79	96.55	146.41	50.28	2198.88	122.28
7	3	2	1	5.51	94.11	219.62	45.59	1769.83	112.63
7	4	1	1	8.86	100.00	209.16	65.03	1877.09	112.63
7	4	2	1	10.28	93.99	334.66	49.61	2037.99	148.02
8	1	1	1	8.79	86.36	177.79	83.13	1823.46	109.41
8	1	2	1	8.58	70.04	345.12	44.25	2467.04	176.98
8	2	1	1	6.83	45.82	209.16	59.66	2198.88	141.59
8	2	2	1	11.29	140.38	240.54	67.71	1555.31	102.97
8	3	1	1	6.22	79.36	135.96	62.35	1179.89	90.10
8	3	2	1	7.38	81.08	261.45	65.70	1930.73	128.72
8	4	1	1	6.77	92.22	125.50	77.09	1126.26	74.01
8	4	2	1	9.03	44.65	407.87	46.26	2198.88	170.55
8	1	1	2	9.76	192.01	125.50	84.47	6328.49	260.65
8	1	2	2	10.24	233.22	167.33	71.06	5309.50	241.34
8	2	1	2	7.97	204.05	230.08	96.54	5041.34	267.08
8	2	2	2	29.44	419.14	303.28	89.16	5041.34	263.87
8	3	1	2	7.18	151.14	188.25	67.04	3968.72	228.47
8	3	2	2	7.79	171.10	156.87	127.37	5738.55	250.99
8	4	1	2	3.81	57.35	146.41	62.35	4665.92	234.91
8	4	2	2	8.44	248.78	167.33	121.34	6006.70	267.08

Appendix table 8 continued. PRS probe measurements at Hyslop Farm in fall 1998.

Date	Block	Rotation	Treatment	NH_4^+-N	NO_3^--N	K^+	PO_4^{3-}-P	Ca^{2+}	Mg^{2+}
				----------μg 10 cm^{-2}----------					
8	1	1	3	7.42	553.29	94.12	126.03	6060.34	250.99
8	1	2	3	10.62	612.00	167.33	103.24	6060.34	260.65
8	2	1	3	6.32	458.09	125.50	123.35	5577.65	302.48
8	2	2	3	9.11	685.54	146.41	105.25	6274.86	299.26
8	3	1	3	6.46	636.13	104.58	129.39	6113.97	276.74
8	3	2	3	6.26	673.37	125.50	122.68	5631.28	238.12
8	4	1	3	8.13	413.15	146.41	123.35	6489.39	289.61
8	4	2	3	12.13	769.32	188.25	116.65	6167.60	279.96

Date: 1 = 10/29/98 2 = 11/5/98 3 = 11/12/98 4 = 11/19/98 5 = 11/26/98 6 = 12/3/98 7 = 12/10/98 8 = 12/17/98
Rotation: 1 = Wheat-oat 2 = Wheat-clover
Treatment 1 = 1 week sampling interval 2 = 4 week sampling interval 3 = 8 week sampling interval

Appendix table 9. Measurements and tissue analysis from one meter of row wheat samples in fall 1998.

Block	Rotation	Treatment	Stand count	DMY†	%N	%C	%P	%K	%Ca	%Mg
			plants m^{-1}	kg ha^{-1}						
1	1	1	57	164.9	4.52	44.51	0.58	3.79	0.46	0.18
1	1	2	79	273.6	4.31	44.97	0.59	3.66	0.35	0.15
1	2	1	116	345.0	4.11	44.51	0.57	3.60	0.44	0.17
1	2	2	102	351.4	4.07	45.01	0.58	3.67	0.40	0.16
2	1	1	64	166.8	3.46	45.51	0.50	3.30	0.35	0.15
2	1	2	80	331.2	4.22	45.44	0.55	3.25	0.30	0.14
2	2	1	56	168.3	4.38	45.26	0.53	3.68	0.38	0.16
2	2	2	71	262.3	4.54	45.31	0.59	3.90	0.36	0.15
3	1	1	41	103.8	4.33	44.98	0.60	3.59	0.40	0.18
3	1	2	76	182.1	5.02	44.82	0.70	4.02	0.39	0.16
3	2	1	63	192.9	4.72	45.31	0.60	3.89	0.41	0.16
3	2	2	66	182.1	5.32	44.52	0.71	4.13	0.39	0.17
4	1	1	86	193.9	3.17	45.71	0.46	2.82	0.36	0.13
4	1	2	53	163.9	5.08	44.64	0.67	3.60	0.37	0.16
4	2	1	54	154.0	4.87	44.10	0.58	3.90	0.38	0.17
4	2	2	49	166.8	4.92	44.70	0.66	4.12	0.38	0.16

†Dry Matter Yield

Rotation: 1 = Wheat-oat 2 = Wheat-clover

Treatment: 1 = 0 kg N ha^{-1} at planting 2 = 20 kg N ha^{-1} at planting

Appendix table 10. Soil test measurements from Hyslop long term rotation plots in fall 1998.

Date	Block	Rotation	NH_4^+-N	NO_3^--N	P	K	Ca	Mg	pH
				----------mg kg^{-1}----------			---cmol kg^{-1}---		
1	1	1	4.9	6.4	122	242	10.6	0.7	6.3
1	2	1	5.0	8.0	128	246	9.7	0.7	6.1
1	3	1	4.5	8.1	125	215	9.9	0.7	6.1
1	4	1	4.4	6.9	120	218	9.0	0.7	6.0
1	1	2	5.5	20.5	117	261	11.2	0.7	6.4
1	2	2	7.0	24.0	124	250	8.6	0.7	5.7
1	3	2	5.6	22.4	127	226	9.8	0.7	5.9
1	4	2	4.6	17.2	111	281	10.1	0.8	6.2
2	1	1	4.3	2.8	132	207	10.8	0.7	6.3
2	2	1	4.0	2.6	133	218	10.0	0.7	6.3
2	3	1	5.2	3.4	133	183	9.8	0.7	6.2
2	4	1	3.6	2.6	127	199	9.2	0.7	6.1
2	1	2	5.7	5.9	110	246	11.2	0.7	6.5
2	2	2	5.5	5.9	122	230	8.2	0.7	5.8
2	3	2	3.7	6.4	140	195	9.9	0.7	6.0
2	4	2	6.5	3.8	132	293	10.4	0.8	6.3

Appendix table 10 continued. Soil test measurements from Hyslop long term rotation plots in fall 1998.

Date	Block	Rotation	NH_4^+-N	NO_3^--N	P	K	Ca	Mg	pH
				----------mg kg^{-1}----------			---cmol kg^{-1}---		
3	1	1	4.3	1.3	151	226	10.7	0.8	6.3
3	2	1	5.9	2.0	130	234	8.1	0.7	5.8
3	3	1	2.8	1.5	136	195	9.6	0.7	6.2
3	4	1	4.1	1.1	149	218	9.3	0.7	6.2
3	1	2	5.5	1.7	130	246	12.5	0.8	6.6
3	2	2	3.4	1.5	150	215	10.3	0.7	6.2
3	3	2	4.5	1.7	152	226	10.1	0.7	6.2
3	4	2	4.3	1.9	143	257	9.7	0.7	6.3

Date: 1 = 10/22/98 2 = 11/19/98 3 = 12/17/98
Rotation: 1 = Wheat-oat 2 = Wheat-clover

Appendix 11. Soil volumetric and gravimetric water contents measured at Hyslop Farm in fall 1998.

			15 cm depth		10 cm depth
Date	Block	Rotation	Vol. Water Cont.	Grav. Water Cont.	Grav. Water Cont.
			---------- % ----------		
1	1	1	-	-	22.8
1	1	2	-	-	24.6
1	2	1	-	-	22.0
1	2	2	-	-	24.1
1	3	1	-	-	21.6
1	3	2	-	-	24.6
1	4	1	-	-	22.3
1	4	2	-	-	24.5
2	1	1	32.90	25.2	24.9
2	1	2	33.30	25.3	25.2
2	2	1	31.60	27.0	26.2
2	2	2	29.90	24.7	25.9
2	3	1	31.90	24.6	24.8
2	3	2	34.30	26.8	28.6
2	4	1	32.60	26.1	25.9
2	4	2	33.10	25.0	27.2
3	1	1	32.16	24.8	24.8
3	1	2	32.22	25.2	25.2
3	2	1	31.72	23.9	24.4
3	2	2	31.22	25.0	26.5
3	3	1	31.58	24.2	24.8
3	3	2	33.48	25.2	26.4
3	4	1	31.50	23.9	24.4
3	4	2	31.16	25.4	25.3
4	1	1	32.04	24.4	26.5
4	1	2	32.96	25.0	25.9
4	2	1	33.00	23.8	25.3
4	2	2	32.02	26.5	26.1
4	3	1	32.16	23.6	25.0
4	3	2	35.48	25.7	27.7
4	4	1	34.06	23.9	25.5
4	4	2	33.26	26.2	27.0

Appendix 11 continued. Soil volumetric and gravimetric water contents measured at Hyslop Farm in fall 1998.

			15 cm depth		10 cm depth
Date	Block	Rotation	Vol. Water Cont.	Grav. Water Cont.	Grav. Water Cont.
			---------- % ----------		
5	1	1	34.50	-	-
5	1	2	35.30	-	-
5	2	1	35.90	-	-
5	2	2	35.40	-	-
5	3	1	36.60	-	-
5	3	2	36.60	-	-
5	4	1	35.50	-	-
5	4	2	36.80	-	-
6	1	1	34.50	-	-
6	1	2	35.80	-	-
6	2	1	36.70	-	-
6	2	2	35.20	-	-
6	3	1	35.90	-	-
6	3	2	37.70	-	-
6	4	1	37.20	-	-
6	4	2	37.70	-	-
7	1	1	34.80	-	-
7	1	2	35.50	-	-
7	2	1	36.20	-	-
7	2	2	36.30	-	-
7	3	1	34.90	-	-
7	3	2	37.80	-	-
7	4	1	36.20	-	-
7	4	2	36.90	-	-
8	1	1	33.90	-	-
8	1	2	34.50	-	-
8	2	1	34.70	-	-
8	2	2	34.90	-	-
8	3	1	35.00	-	-
8	3	2	36.00	-	-
8	4	1	35.70	-	-
8	4	2	36.40	-	-

Date: 1 = 10/29/98 2 = 11/5/98 3 = 11/12/98 4 = 11/19/98 5 = 11/26/98
6 = 12/3/98 7 = 12/10/98 8 = 12/17/98
Rotation: 1 = Wheat-oat 2 = Wheat-clover