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DISTRIBUTION OF COVER CROP NITROGEN RETAINED BY SOIL AGGREGATES WITHIN A RYE-CORN AGROECOSYSTEM

By

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ABSTRACT

DISTRIBUTION OF COVER CROP NITROGEN RETAINED BY SOIL AGGREGATES WITHIN A RYE-CORN AGROECOSYSTEM

By

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Decomposition of rye root and shoots and their contributions to soil N, its location within soil aggregates, and uptake by succeeding corn were monitored using two different field experiments in a Kalamazoo loam soil. Experiments were conducted at the LTER Interactions Sites and Microplots at the Kellogg Biological Station in Southwest Michigan from November 1997 to November 1999. Four main treatments were considered at the Interactions sites: Conventionally tilled with N fertilization (CT-F), conventionally tilled with no N fertilization (CT-NF), no tillage with N fertilization (NT-F) and no tillage with no N fertilization (NT-NF). Each plot was split in half with a rye cover crop planted on the west one half of the 16 plots. Sixteen microplots consisted of four treatments: bare fallow (C), bare fallow with rye shoot (RS), rye root (RR), and rye root plus shoot (RRS).

Rye plants were labeled with ^{15}N by foliar applications of solutions containing 6.39 g $(^{15}NH_4)_2SO_4$. ^{15}N enrichments of soil aggregates between 2.0–4.0, 4.0-6.3 and 6.3-9.5 mm across were determined after residue application. Concentric layers of aggregates were removed from each aggregate by newly designed meso soil aggregate erosion (SAE) chambers.

Deep soil samples (to 150 cm) were collected to determine extractable inorganic N contents. Volumetric soil water contents were measured by time domain reflectometry (TDR). Non-destructive development of roots was monitored by minirhizotron technology. Suction lysimeter samples for soluble N content. Destructive soil samples were collected to extract roots to determine root biomass, N and C. Corn yield and rye biomass were monitored each year.

Rye root uptake of residual soil N reduced inorganic N leaching from the soil profile. During the 2-year study, cover crop management greatly reduced the quantities of inorganic N lost below the rooting zone of a Kalamazoo loam soil. Dual spray applications of Roundup herbicide to Roundup-ready corn, planted directly into decomposing rye cover crops, resulted in the contributions of at least 28 kg N per ha (NT-NF) to 41 kg N per ha (NT-F) to the 1998 corn crop. Reducing nitrogen losses to groundwater beyond the root zone by 27 to 73 kg N per ha during the year. Leaching losses of N from fertilized CT-F treatments were 60 kg N per ha greater than N losses from NT-F treatments. Negative linear correlations were observed between extractable inorganic N contents and root length, volume and surface area in Ap horizons of all treatments. Results suggested that rye roots reduce N leaching from the soil profile primarily by absorbing N and plugging macropores reducing leaching losses from the Ap horizon of a Kalamazoo loam soil.

Rye roots deposited N to the surfaces of soil aggregates more rapidly than did rye shoots. Concentration gradients of recently derived rye N, within soil aggregates increased with aggregate size. Recently generated rye plant N was

retained by exterior layers with little accumulating within interior regions of soil aggregates larger than 4 mm. Yields became more dependent on location of N within aggregates when soil aggregate size and N gradients increased. Highly significant correlations were observed between changes in the ratios of N, comparing N located on exterior layers to N located within interior regions of soil aggregates, 6.3-9.5 mm across, and corn biomass, r^2=0.88 for no cover crop and 0.71 for rye cover crops in 1999. Recovery of rye shoot-derived ^{15}N by corn averaged 8% during this 2-year study. Rye roots contributed nearly 12 kg N ha^{-1} to the succeeding corn crop and rye shoots contributed nearly 4 kg N ha^{-1} N to succeeding corn crops at Microplots. Rye roots plus shoots contributed slightly more than 15 kg N ha^{-1} during the two-year study.

Soil aggregates from rye cover crop treatments were much more resistant to erosive forces applied to the external and transitional concentric layers by the SAE chambers than soil aggregates from no rye cover crop treatments. Erosion rates of soil layers were reduced 2-10 fold by rye cover crop treatments. Smaller soil (2.0-4.0 mm) aggregates were much more resistant to erosion than larger (6.3–9.5 mm across) aggregates. Transitional layers of soil aggregates were more resistant to erosion than exterior layers of soil aggregates.

In summary, short-term contributions of rye root and shoot N can be identified more rapidly when soil aggregates are peeled into different concentric layers and analyzed. Nitrogen flux rates and stability changes among the concentric layers and internal regions were reported within soil aggregates greater than 4 mm across. These gradients were identified in larger but not

smaller soil aggregates and suggest alternative models are needed for predicting the formation of soil aggregates. Rye roots successfully reduced nitrate leaching from a Kalamazoo loam soil. Mineralization of N from decomposing rye roots supplied three times more nitrogen to succeeding corn plants.

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CHAPTER 1

DISTRIBUTION OF COVER CROP N RETAINED BY SOIL AGGREGATES IN RYE-CORN AGROECOSYSTEM

INTRODUCTION

Plants obtain nitrogen from sources of applied N fertilizers, mineralized soil organic matter (SOM) N, inorganic soil N and, biologically fixed atmospheric N_2. Although mineralization of SOM provides some available N for uptake by plants, the rate of N mineralization produces inadequate supply of N for maximizing corn yields. Nitrogen fertilizers provide the majority of plant-available N, varying from 17 to 80 % depending on rate and time of fertilizer applications (Meisinger et al., 1985, Karlen et al., 1998). The amount of N fertilizer recovered by plants at harvest was 25 to 56 % (Jokela and Randall, 1997). Therefore, approximately 50% of applied N remained in the soil and becomes available for leaching, volatilization and denitrification.

The amount of NO_3-N found in the groundwater is often related to the amount of N fertilizer applied to crops (Hallberg, 1986). Nitrate leaching depends on soil texture, amount and frequency of precipitation, fertilizer management, irrigation and N transformations in soils (Smith and Cassel, 1991). Therefore soil N is best managed using systems that maximize nitrogen (N) fertilizer absorption efficiency and minimize leaching of NO_3-N into groundwater.

Cover crops can be used to improve management systems, which reduce leaching and build SOM through continuous additions of cover crop residues in the early spring. Effectiveness of cover crops to reduce leaching depends on its ability to uptake soil N when the temperature is low. Rye, ryegrass, winter wheat and rape can uptake residual N during the cold season (Martinez and Guirarud, 1990). Rye, ryegrass and other non-leguminous cover crops remove NO_3 from the soil more efficiently than some of the leguminous cover crop (Meisinger et al., 1991, Shipley et al., 1992, Groffman et al., 1986). Ranels and Wagger (1997) reported that a rye-crimson clover mixture was capable of recovering greater residual soil N than only crimson clover monoculture, but less than a rye monoculture. However, Rasse et al., 1999, reported that alfalfa removed soil inorganic N efficiently and alfalfa crown and roots contained an average of 115 kg N ha^{-1}.

Decomposition of cover crop residues (Wagger et al., 1998), residue N release (Ranells and Wagger, 1992) and uptake of N released by cover crops by a succeeding crop (Clark et al. 1994, Hargrove, 1986) have been investigated, however, little attention has been given to root system contributions to these N mineralizations. These effects and the importance of roots must be considered in agricultural systems and in nutrient cycles. In general, the root biomass of annual cover crops are a relatively small portion of the total biomass, but their total contributions across longer periods of time are very influential and important forms of C which enhance soil physical, chemical and biological properties and processes. Rye established early in fall and had greater root development

compared to hairy vetch from November to April (Upendra et al., 1998). These rye roots can plug macropores in soil profile and reduces NO_3 leaching during the rainy season. Ditsch et al., 1993, reported that on a silt loam soil winter rye was effective cover crop for accumulating large quantities of residual N, NO_3-N and NH_4-N derived from fertilizers and native mineralization of SOM.

Rye grows and matures rapidly in spring. Consequently the timing of spray-killing the rye is a very important management factor. If rye is killed too early, soil water contents can be conserved, yet intense spring rains can dramatically leach excess NO_3 into the groundwater. Spray-killing a rye cover crop several weeks before no-till corn planting resulted in more N availability to succeeding corn plants (Vaughan and Evanylo, 1998). Late spring applications of herbicides to a rye cover crop can reduce available soil moisture, produce excessive biomass which limits seed contact with soil, reducing plant populations and corn yields. Termination of rye cover crop at the time of soybean planting resulted in soil water depletion by the rye, which delayed emergence of soybean (Campbell et al. 1984). Wagger (1989) reported that average rye biomass increases 39% for every 2 weeks delay. Late desiccation of rye just before no-till corn planting increased soil, fertilizer and rye N immobilization (Vaughan and Evanylo, 1998). After termination of cover crop, much of this cover crop N may be partly returned via plant decomposition and mineralization of plant residues for subsequent crop uptake (Wagger et al., 1985). Cereal cover crops can serve as a sink-source for soil N. Decomposition of rye root and shoot residues, their by- products and living rye roots effect on soil nutrient cycle and aggregate

stabilization and formation. Kladivko (1994), reported that, microbial decomposition of fresh organic material is one of the main contributors to aggregate stabilization in the soil. Microorganisms decompose organic residues, producing polysaccharides and other compounds that bind soil particles together into aggregates. Recently the availability of Round-up ready corn has provided another opportunity for expanding the use of rye cover crop management to retain more soil N. If only a small boarder of the rye cover along the corn row is killed at the time of corn planting and rest of the rye remains between the corn rows, living rye roots plug macropores and reduce nitrate leaching from the soil. After the 2nd or 3rd leaf stage of corn, when corn roots start to develop, broadcast applications of Round-up across the entire plot, develops a strategic timing for release of cover crop N for the direct utilization by the succeeding corn crop.

Numerous studies on the formation, stabilization, and effect of different soil and crop management systems on soil aggregation have been reported (Wood et al., 1991, Roberson et al., 1995). However, there is little information about the location of recently decomposed plant residues within soil aggregates (Angers et al., 1997). Growth of plant roots and development of soil aggregates conversely affect each other. Soil contains cracks and planes of weakness between aggregates. Roots preferentially grow in these cracks and on the aggregate surfaces rather than within the aggregates. (Whiteley and Dexter, 1983). The root systems of grasses are extensive and their position is generally inter-aggregate (Allison, 1973). Living roots influence the chemical and biological properties of rhizosphere soil (Fisher et al., 1989). Since roots preferentially grow

around the aggregate surfaces, rhizosphere effects are greater on the surfaces of the aggregates. Roots control the concentrations and fluxes of soil N by absorbing soil water and soluble N compounds (Harper et al., 1995 and Frensch et al., 1996). Released N *in situ*, from decomposing plant roots and shoots contribute to stabilizing soil aggregation processes (Oades, 1993). Dead roots act as a readily decomposable SOM and cause increased oxygen consumption in rhizosphere (Fisher et al., 1989). Root exudates modify the solubility, sorption and transport of ions to the root surfaces, affect the microbial activity. N is deposited in the rhizosphere as NH_4, NO_3, and root debris. The amount of N deposited in the rhizosphere of wheat was up to 20% of total plant N (Janzen, 1990 and Janzen and Bruinsma, 1993). Excreted of plant available N forms and mineralized N from rhizodeposits may be reabsorbed by the plant.

Clay illuviation, preferential movement of water, weathering of clay and preferential growth of roots, can change biogeochemical properties of aggregate surfaces (Smucker et al., 1997, Whiteley and Dexter, 1983, Wilcke and Kaupenjohann, 1998). Center of aggregates contain less oxygen than the aggregate surfaces (Sierra and Renault, 1996, Sextone et al., 1985, Hojberg et al., 1994). Therefore nitrogen transformations can be varied between aggregate interiors and surfaces (Seech and Beauchhamp, 1988)

Recent studies showed that aggregates develop by adding concentric layers of cations, carbon (Santos et al., 1997, Horn 1990, Smucker et al. 1997, Dell et al., 1999) and heavy metals (Wilcke and Amelung, 1996). These short-term effects of cropping on SOM can be determined when concentric layers are

removed from soil aggregates. Angers and Mehuys (1989) found that 2 yrs of alfalfa and barley resulted in 15-25% larger carbohydrate contents compared to fallow or corn and 46 – 83% more carbohydrates compared to fallow treatment (Angers and Mehuys, 1990). Six weeks after planting ryegrass seeds, exterior layers of soil aggregates had 20% and interior region of soil aggregates had 8% of new C_3-C (Santos, 1998). Therefore, under cover crop rotation, recently derived rye cover crop shoot and root nitrogen should be deposited at greater concentrations on the surfaces of soil aggregates. To understand cover crop N contributions to succeeding plant and soil aggregation, N sources and location in the soil must be identified. In this research, the contributions of roots and shoots on soil N pool were measured separately.

Labeled rye shoot and root residues can be used in order to distinguish between soil N and residue derived N. Using stable ^{15}N can be a very effective tool to determine the location of rye root and shoot derived N in soil and succeeding plant. ^{15}N stable isotopes have been used in soil-plant systems to investigate nitrogen transformations (Davidson et al., 1991), biological N fixation, natural abundance (Yoneyama et al. 1990), fertilizer utilization (Angle et al. 1993), mineralization and immobilization (Davidson et al., 1991 , Shen et al. 1984, Stephen and Myrold, 1996), denitrification (Blackmer and Bremner, 1977), plant uptake (Thomsen, 1997), leaching (Hallberg, 1986). Isotopic tracers used in plant and soil studies should have similar reaction rates as the ion to be studied (Menzel and Smith, 1983). The ^{15}N stable isotope is ideal for tracing N through the plant- soil-microbial pathways associated with soil aggregation and

soil nitrogen processes. Field and lysimeter experiments give more realistic estimations of N transformations and their direct measurement of N recovery than laboratory experiments (Lazzari, 1982). Most studies on ^{15}N labeled residue-decomposition and associated nitrogen transferred to the following crop have used dried plant shoots, stems and sometimes roots. Some researchers determined N uptake from root residues by succeeding plants however they first extracted roots from pots or microplots and then incorporated into the soil (Harris and Hesterman, 1990, and Norman et al., 1990), Hubbard and Jordan, 1996 reported ^{15}N recovery of corn from labeled soil plus wheat root mix and they could not identify the direct recovery from roots only. Stevenson, (1998) used on indirect approach to estimate legume root derived N to the succeeding plan. Few studies used *in-situ* labeling of plant material such as foliar N-fertilization in the field (Zebarth et al., 1991, Jordan et al., 1996).

The objectives of this dissertation research were;

1. To develop a two stage herbicide spray killing control of the rye cover crop and determine N retention within the soil profiles of corn grown in conventional tillage (CT) and no tillage (NT) management systems of a Kalamazoo loam.
2. To determine relationships between cover crop root systems and soil mineral N contents within the profile of a Kalamazoo loam soil.
3. To identify the contributions of rye root and shoot N to different regions of concentric layers within aggregates ranging from 2.0 to 9.5 mm across in the A_p horizon of a Kalamazoo loam soil.

4. To determine recovery of N from rye roots and shoots by a succeeding corn crop.

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CHAPTER 2

SOIL N CONSERVATION BY ROOTS AND SHOOTS OF A RYE COVER CROP AND RELEASED TO A SUBSEQUENT CORN CROP

ABSTRACT

Effects of rye root and shoots and their time of desiccation on soil inorganic N were monitored in a Kalamazoo loam soil. Experiments were conducted at Microplot and Interaction Sites of Kellogg Biological Station in Southwest Michigan from November 1997 to November 1999. Four treatments were used at Interactions sites: Conventionally tilled and N fertilized (CT-F), conventionally tilled and non fertilized (CT-NF), no tilled and N fertilized (NT-F) and no tilled and non fertilized (NT-NF). Microplots consisted of four treatments: bare fallow (C), bare fallow with rye (*Secale cereale L.*) shoots applied as surface mulch (RS), *in situ* rye roots (RR), and *in situ* rye roots plus shoots applied as a surface mulch (RRS). Soil samples were collected to depths of 150 cm for extractable inorganic N contents. Volumetric soil water contents were measured by time domain reflectometry (TDR). Non destructive developments of roots were monitored by minirhizotron technology. Soil solution samples were collected by suction lysimeters.

Rye root and shoot uptake of residual soil N reduced inorganic N leaching from the soil profile. During the 2-year study, cover crop and tillage influenced the

amounts of inorganic N lost below the rooting of the Kalamazoo loam soil. Dual spray applications of herbicide to Roundup-ready corn, planted directly into decomposing rye cover crops, resulted the cover crop contributions of at least 28 kg N per ha (NT-NF) to the successive corn crop reducing nitrogen losses to groundwater below the root zone by 27 to 73 kg N per ha during the entire year. N leaching from CT treatments was 60 kg ha^{-1} y^{-1} greater than those from NT treatments when they were fertilized with N. Leaching losses from non-fertilized CT-NF treatments were 27 kg N ha^{-1} y^{-1} greater than those from NT-NF treatments. Using rye cover crops between two successive corn crops had no significant affects on corn yields.

INTRODUCTION

Plants obtain nitrogen from sources of applied N fertilizers, mineralized soil organic matter (SOM) N, inorganic soil N and, biologically fixed atmospheric N_2. Although mineralization of SOM provides some available N for uptake by plants, the rate of N mineralization produces an inadequate supply of N for maximimum corn yields. Nitrogen fertilizers provide the majority of plant-available N, varying from 17 to 80 % depending on rate and time of fertilizer applications (Meisinger et al., 1985, Karlen et al., 1998). The amount of N fertilizer recovered by plants at harvest was 25 to 56 % (Jokela and Randall, 1997). Therefore, approximately 50% of applied N remained in the soil and becomes available for leaching, volatilization and denitrification.

Increasing quantities of NO_3 have been accumulating in the groundwaters of Michigan during the past 3 or 4 decades, causing groundwater wells in Michigan to exceed 10 mg NO_3 L^{-1}, the maximum concentration permitted for potable water by the EPA. In Kalamazoo County, Michigan water sampled from 6 of 46 wells contained NO_3-N levels above the EPA limit of 10 mg L^{-1} (Rheaume, 1990). In Van Buren County, 22% of the wells tested had nitrate concentrations that exceeded the EPA limit. Nitrogen inputs in Van Buren County were deemed to be 72.7% from fertilizer, 21.3% from precipitation, 4.5% from animal wastes, and 1.5% from septic tanks (Cummings et. al., 1990). Water containing nitrate concentrations greater than 10 mg L^{-1} is considered unsafe for infants, including

for use in mixing of baby formulas. Nitrate causes methemoglobinemia, the cause of bluish coloring in babies and may be fatal unless properly treated.

Quantities of NO_3-N in the groundwater are often directly related to the rates and timing of N fertilizer applications, soil texture and tillage of nearby soils (Hallberg, 1986; Meisinger et al., 1985), the amounts and frequencies of precipitation, crop rotation (Weed and Kanwar., 1996), as well as irrigation scheduling and N transformations in the soil (Smith and Cassel., 1991). Reductions in the application of N fertilizers are often viewed as a major cause for lower crop yields. Therefore, the best management of soil N is when crop production systems efficiently utilize added N with minimal leaching of NO_3-N into groundwater.

Rapid growth of cold-tolerant cover crops improves the retention of soil N in cash cropping systems. Roots of actively growing rye or wheat cover crops reduce leaching of nutrients and build soil organic matter through the addition of residues (Kuo et al., 1997). They also reduce surface crusting, increase infiltration thereby decreasing erosion of surface soils, especially in the early portion of the Spring (Kessavalou and Walters, 1999). Rye, ryegrass, winter wheat and hairy vetch uptake residual N during the rainy cold seasons between cash crops in Europe (Martinez and Guirarud, 1990), the Atlantic coast of the U.S. (Shipley et al., 1992), in Eastern Canada (Raimbault et al., 1991), and many midwestern regions of the U.S (Vaughan and Evanylo, 1998). Ditsch et al., 1993, reported that on a silt loam soil, winter rye (*Secale cereale L.*) was an effective cover crop for accumulating both NO_3-N and NH_4-N which were N residues of N

fertilizers. Therefore, the utilization of cereal cover crops between cash crops are of great interest to farmers in Michigan. Rye appears to be the most suitable cover crop for Michigan soils because it can be easily established late in the Fall and it is resistance to the long harsh winter climate.

Legume and non-leguminous crops have been reported to successfully uptake residual soil N between cash crops. Rasse et al. (1999) demonstrated, that once established, alfalfa removed nearly all nitrates from 0-60 cm profiles of Kalamazoo loam soils in southern Michigan. Cereal grasses, which can be established more easily than legumes, have been reported to be more efficient in the uptake of residual soil N than legumes when both have been compared as winter cover crops (Meisinger et al., 1991, Shipley et al., 1992, Groffman et al., 1986). McCracken et al., (1994) reported that rye reduced NO_3 leaching by 94%, compared with 48% for hairy vetch. Nitrogen contents of small grain cover crop residues varied ranging from 25 to 50 kg N ha^{-1} (Reeves, 1994).

Rye quickly established in the fall and had greater root development compared to hairy vetch from November to April (Upendra et al., 1998). These root systems can plug some of the macropores throughout the soil profile and both uptake and plugging reduces water flow and NO_3 leaching.

Rye growth and biomass production is rapid in early spring. Strategically timing the killing of rye is a very important management factor. If rye is killed early, soil moisture can be conserved. However, if rye is killed too early excessive spring rains will enhance NO_3 leaching. Untimely late killing of rye results in soil moisture losses for succeeding cash crops. Excessive production

of cover crop shoot biomass will interfere with seed to soil contact at planting, reducing seed germination (Mehdi et al., 1999). In sub-humid and humid regions cover crops should be permitted to grow until they produce sufficient above ground biomass to cover the soil surface and maximize root proliferation, yet terminated early enough to maintain adequate soil profile water storage prior to planting the next crop (Unger and Vigil, 1998). In Michigan, cover crop residues on the surface must be managed so that they do not reduce soil temperature but provide increased conservation of surface soil well into the growing season of the next crop.

Spring suppression of rye by applications of small quantities of glyphosate herbicides resulted in higher corn dry matter (44%) at harvest than when the rye biomass was not chemically killed (Morris et al., 1998). Recently the availability of Round-up ready corn has provided another opportunity for expanding the use of rye cover crop management to retain more soil and cover crop biomass N. If only the rye cover on the corn row is killed at the time of corn planting and rest of the rye remains viable between the corn rows until the entire rye cover crop is killed by Roundup. These living rye roots between rows, reduce soil nitrate leaching by plugging soil macropores and absorbing soil nitrates. Strategic band placement of herbicide provides continued protection of soil between the rows, initiates slow N release of biomass N from the rye cover crop at the row and provides continuous N absorption by the rye cover across more than 65% of the soil surface between rows.

These concepts led us to develop a two-year field experiment with the following objectives:1)To develop a strategic two-stage herbicide spray-killing control of the rye cover crop in N-fertilized conventional tillage (CT) and no tillage (NT) management systems of a Kalamazoo loam.

2)To identify dependent relationships between rye cover crop root systems and soil mineral N contents within the profile of a Kalamazoo loam soil.

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MATERIALS AND METHODS

Experimental design and treatments at Interactions site

Field treatments were incorporated into 16 plots, 40 x 27 m, of the Interactions site on a Kalamazoo loam soil (coarse-loamy, mixed, mesic Typic Hapludalf), established in 1986 at the KBS/LTER site near Kalamazoo, Michigan. Treatments were replicated four times in a randomized complete block design. Treatments consisted of: 1) conventional tillage and nitrogen fertilization (CT-F), 2) no tillage and nitrogen fertilization (NT-F), 3) conventional tillage and no fertilization (CT-NF), and 4) no tillage and no fertilization (NT-NF). Conventional tillage (CT) plots were moldboard plowed, and two of the associated four large natural lysimeters (Rasse, 1997) were manually tilled to 20 cm by a shovel in the Spring of 1998 and 1999.

Each field plot (27 x 40m) was split in half. Cereal grain rye (*Secale cereale, L.*) was drilled in the west one-half (13.5 x 40 m) of each plot at the rate of 81 kg ha^{-1} in the Spring of 1998 and broadcast applied at the same seeding rate in the Fall of 1998. Following deep sampling of the soil profile and rye biomass measurements, conventional tillage plots were plowed on May 5, 1999 incorporating the cover crop into the soil. Urea nitrogen fertilizer (46-0-0) was broadcast applied at the rates of 150 kg N ha^{-1} to the 8 fertilized (F) plots on May 7, 1999. Then CT plots were disced and cultivated following fertilizer application.

Roundup-ready corn, Dekalb 493 (*Zea mays,* L.), was planted in rows (spaced at 70 cm) at the rate of 71,136 seeds per hectare on June 6, 1998 and May 9, 1999. Immediately following corn planting, narrow strips (25 cm wide)

were sprayed in both the CT and NT treatments and rye plants in the corn rows were killed with these band spray applications of Roundup (glyphosate) Ultra, without ammonium sulphate (4.5 L ha^{-1}). Roundup (4.5 L ha^{-1}) and Atrazine (4.5 L ha^{-1}) were broadcast sprayed, using 187 L ha^{-1} of water, to kill the remaining rye cover crop on each plot. Herbicide applications were split in two different times in 1998. Half of the rye planted plots (9 corn rows in an area 6.75 x 40 m) were broadcast sprayed at the 2^{nd} leaf stage of corn growth and the other half was sprayed at the 4^{th} leaf stage of corn. Rye was taller than the young corn seedlings as it had begun heading at the 4^{th} leaf stage of corn. Soil inorganic N contents at the 2^{nd} and 4^{th} leaf stages did not change significantly. In order to not risk corn yield reductions during the second year, band strips, 25 cm wide, of rye were killed at corn planting with applications of Roundup Ultra, without ammonium sulphate (4.5 L ha^{-1}) and all plots were broadcast sprayed at the 2^{nd} leaf stage of corn growth with Roundup (4.5 L ha^{-1}) and Atrazine (4.5 L ha^{-1}), using 187 L ha^{-1} of water. Rainfall during the months of May was 119 mm in 1998 and 153 mm in 1999. Summer rainfall in June and July of 1998 were 178 mm, well below the 30-year average (193.04 mm). In 1999, June and July totals were even lower, 157 mm at KBS. Consequently, 38 mm of irrigation water were applied to all plots by an overhead traveling gun on July 1999. Corn crops were harvested on October 28, 1998 and October 27, 1999.

Instrumentation at Interactions site

Two suction lysimeters (Model 1900, Soil Moisture, Santa Barbara, CA) equipped with porous ceramic cups with a 1 bar air-entry value, 4.8 cm diameter and 91 cm long, were installed into the middle of each Bt_2 horizon, averaging 60 cm deep, at 45° angles to the soil surface. Suction lysimeters were located in the 7^{th} or 8^{th} row, at 2 meter spacings, of each fertilized NT-F plot in 1998 and in each fertilized NT-F and CT-F plot in 1999. Vacuum (~ 20 inches of mercury) was applied to each suction lysimeter 24 to 30 hours before soil solutions were sampled, by using either manual or electrical vacuum pumps. Solution samples, ranging from 10 to 20ml, were extracted and stored in plastic scintillation vials at 4°C. NO_3 and NH_4 contents were analyzed by the cadmium reduction method using a QuickChem Automated Ion Analyzer (Lachat Instruments, West Mill Road, Milwaukee, WI).

TDR probes were inserted horizontally into each Bt_2 horizon (at the same depth as the suction lysimeters) in rye and no rye plots of all 16 plots. Horizontal installations of 20 cm TDR probes were facilitated by digging small trenchs, 50 to 60 cm in width and between the corn rows, to the middle of each Bt_2 horizon. The TDR probes were inserted horizontally, directly below the corn row by pushing probe into the soil immediately following planting. The cable of each TDR probe was brought to the soil surface and soil profiles were recompacted, horizon by horizon, to approximately their original densities. The TDR probes consisted of three stainless steel wave guides (0.5 cm diameter x 20 cm length) and were constructed at the Soil Biophysics Laboratory, Michigan State University, MI,

U.S.A, as described by Huang (1995). Cable tester meter readings were collected from the TDR cables at the soil surface using a Tektronix cable tester (Model 1502C, Tektronix Inc, Beaverton, Oregon, U.S.A.). Volumetric soil water contents were calculated using the equation by Topp et al. (1980) as described below:

$$Qv= [-5.3 \times 10^{-2} +(2.92 \times 10^{-2} * K_a)-(5.5 \times 10^{-4} \times K_a^2)+(4.3 \times 10^{-6} \times K_a^3)] \times 100 \quad [1]$$

Where:

Ka is the apparent dielectric constant and $Ka=ct/L^2$,

t is the signal travel time in nanoseconds,

t = (B-A)/(Vp x c),

c = Propagation velocity (Vp) of an electromagnetic wave in free space and c= 30 cm/nsec,

Vp = 0.99,

L = Length of the transmission line or waveguide probe (20 cm)

A = Distance in feet, of the TDR cable from the TDR wave guide probes to the pulse generator,

B = Distance in feet that the reflected pulse is from the pulse generator.

Root growth, demographics and dynamics were monitored *in situ* by minirhizotrons (Upchurch and Ritchie, 1983; Smucker et al., 1987). Two minirhizotron tubes (0.05 x 2.4 m) were inserted in the soil, directly under the corn row, to depths of 106 cm at 45° angles in both rye and no rye cover crops of the 8 fertilized plots. The objectives of this study did not require the installation of

MR tubes into non-fertilized (NF) plots. Micro-video color camera (Bartz Technology Co., Santa Barbara, CA), equipped with an index handle and color monitor, were used to video record root images intersecting the upper 1.8 x 1.35 cm region at each stop along the MR tube. Root images were digitized and processed by the computer algorithm MR-RIPL, version 3.0, using a Sun Ultra 2.0 in the Root Image Processing Laboratory (RIPL), at Michigan State University. Internet address of the site is http://www.rootdig.css.msu.edu.

Experimental design and treatments at Microplots site

A two-year field experiment (1997-1999) was conducted on 16 microplots (6 by 10m) established in August 1994 (Rasse, 1997) on a Kalamazoo loam soil (coarse-loamy, mixed, mesic Typic Hapludalf) at the KBS/LTER site in southwestern Michigan. There were four treatments:

1) Bare soil control (C);

2) Bare soil fallow, where rye shoots were applied as soil surface mulch, before corn planting (RS);

3) Rye cover crop roots, where shoots were cut and removed and roots remained *in situ* in the soil (RR);

4) Rye cover crop roots and shoots, where rye shoots were cut and returned to the soil surface as a mulch and the roots remained *in situ* in the soil (RRS).

Each treatment was replicated four times in a randomized block design. The previous crop from August 94 to April 97 was alfalfa (Rasse, 1997). The alfalfa

was spray-killed with a Roundup Ultra application in April 1997 and plots were maintained plant free, by two additional applications of Roundup Ultra during the successive seven months. Rye was seeded at the rate of 81 kg ha^{-1} by broadcasting seed onto the soil surface in late October 1997 and at the rate of 162 kg ha^{-1} in mid September 1998. Following a severe open winter, an additional seeding of rye was broadcast applied on April 7, 1998 to better establish a complete rye cover crop on each plot, at the rate of 81 kg ha^{-1}. Finely ground limestone was applied to all plots at the rate of 2 tons/ha on April 4, 1998. No limestone was applied in the Spring of 1999.

All plots were broadcast sprayed with Roundup (glyphosate) Ultra without ammonium sulphate (4.5 L ha^{-1}) ,mixed with water using 186 L ha^{-1} to kill cover crops and weeds approximately two weeks before corn planting.

Corn was planted at the rate of 64,220 seeds ha^{-1}, at 70 cm row spacing, on June 6, 1998 and May 17, 1999. When corn growth was at the fifth leaf stage, the 16 main plots, except the two ^{15}N lysimeters in each plot, were side dressed with of 150 kg N ha^{-1} of NH_4NO_3. In July 1999, 38 mm of irrigation water were applied to all plots using a traveling gun sprinkler irrigation system. Corn was harvested in September of 1998 and 1999.

Instrumentation at Microplots site

Non destructive sampling of soil solutions, using *in situ* instruments of 3 suction lysimeters, soil water by 3 TDR probes and root dynamics by video recording 2 MR, were completed on a regular basis using these instruments which

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had been previously installed in NE quarter of each plot by Rasse (1997). Polyvinyl chloride (PVC) cylinders (30 cm in diameter and 60 cm in depth) installed to soil depths into the middle each Bt_2 horizon (~60 cm) in the NW quarter of each plot, served as lysimeters for containing the ^{15}N labeling study. Destructive deep profile soil sampling was limited to the SW quarter of each plot. Corn yields samples were taken from the SE quarter of each plot. Each of the 16 plots were isolated by a black garden boarder surface plastic barrier, installed to depths of 10 cm with 5 cm remaining above the soil surface to prevent run-off and run-on between plots. A one-meter border was reserved around each plot.

Each field plot was equipped with three suction lysimeters were installed to soil depths of 15, 35 and 60 cm at 45° to the soil surface. Water samples were collected from suction lysimeters 24 to 30 hrs following application of vacuum as described above. Samples were stored and analyzed for NO_3 and NH_4 as described above.

Soil water contents of each horizon were estimated by TDR wave-guides installed at the same depths as the three suction lysimeters, as described by Rasse, (1997). Root dynamics were monitored nondestructively and image processed by the RIPL, as described above. Since MR tubes were installed before (Rasse, 1997) each rye planted plots had 3 MR tubes and each no-rye planted plots had 1 MR tube. In this experiment an additional MR tube was installed in the bare plots to obtain duplicate root images in the C and RS plots. Root images were taken from the 2 MR tubes from each field. Root surface areas

and volumes were calculated as a sum of all areas and volumes for all width classes. Formula [1] was used to calculate root surface area:

$$A = 2\pi[(r_1 \times l_1) + (r_2 \times l_2) + \ldots (r_5 \times l_5)] \quad [1]$$

Where:

A is the root area (cm^2),

R_n = are the respective root radii (cm) for the five root width classes,

L_n = total length of root segments for each width class (cm).

The formula used to calculate root volume was:

$$V = \pi[(r_1^2 \times l_1) + (r_2^2 \times l_2) + \ldots\ldots (r_5^2 \times l_5)] \quad [2]$$

Where:

V is the volume (cm^3),

r = root radius (cm) for each width class,

l = total root length of root segments for each width class (cm).

Plant measurements

Interactions site Rye subsamples (1 m^2) were harvested prior to corn planting, oven dried at 70° C and rye biomass was calculated per ha. Corn plants were sub-sampled to determine total dry biomass of each of the 32 plots from an area of 2.1 m^2 in July 1998 and 1999, dried and weighed and dry corn biomass was calculated per ha. Total corn biomass (stalk + ear) for subsamples (2.1 m^2) and grain yield for each plot were determined for in early September and at the 1998 harvest. Total corn biomass (stalk + ear) for subsamples (10.64 m^2), and

grain yield for each total plot were also determined in early September and at the 1999 harvest. To determine water content of the grain, 500 g subsamples were taken from each of the 32 plots and oven dried at 70°C. All rye and corn plant materials were oven dried at 70°C. Plants were finely ground to pass through a 0.5 mm screen, mixed thoroughly and subsamples ranging from 5 to 7 mg were weighed to 5 decimal places and recorded before transferring into small tin capsules and placed into the autosampler. Total C and N were determined by the dry combustion method (Kirsten, 1983) using a C/N/H analyzer (Model NA 1500, series 2, Carlo Erba Stumentazione, Milano, Italy).

Microplots site: Rye subsamples (1 m^2) were harvested prior to corn planting and rye biomass per ha was calculated. Total corn biomass (stalk + ear) and grain yields were subsampled from the middle 2.1 m^2 of each plot immediately before each of the 1998 and 1999 harvests. Aboveground biomass, C and N contents of the corn grain and stalks plus leaves were determined as described above.

Soil measurements

Interaction and Microplot sites: Soil samples were taken from the main field plots of both experimental sites to depths of 150 cm in the early spring, mid summer and fall, following corn harvests in 1998 and 1999, using a hydraulic probe which forced a metal core (8.9 cm diameter) vertically into the soil (Giddings Machines Co., Ft. Collins, CO). Two core samples were taken from

each plot. One sample was taken from the corn row and another sample was taken adjacent to first sampling row, but midway between the rows. Soil cores were divided into A_p (average thickness of this horizon was 31 cm), Bt_1 (~18 cm), Bt_2 (~13 cm), C_1 (~52 cm) and C_2 (~37+) horizons. Each core was vertically divided into two halves. One half of each sampled horizon was stored at 4°C until roots were washed free of soil and other half was used for analyses of inorganic N extraction. Rye and corn roots were extracted from the soil matrix by hydropneumatic elutriation (Smucker et al., 1982). No effort was made to neither identify nor separate roots from rye or corn. Subsamples of extracted roots (~30 mg) were taken for total N and C analysis. Subsamples were oven dried at 70°C for 24 hrs. Roots were finely ground to pass through a 0.5 mm sieve, mixed thoroughly and sub samples (5 to 7 mg) were weighed into small tin capsules and placed into the autosampler. Total C and N was determined by the dry combustion method of Kirsten (1983) using a C/N/S analyzer (Model NA 1500, series 2, Carlo Erba Stumentazione, Milano, Italy). The remaining portion of the washed root samples were stored in labeled Whirlpack plastic bags at 4ºC containing 20% (v/v) methanol solution. To quantify their morphological parameters, roots were uniformly distributed on a clear plastic square (9.4 x 9.4 cm) Petri dish. To avoid overlapping roots, large root samples were split into 2 or more dishes before scanning. Surfaces of roots were covered with a thin water film, distributed evenly across the Petri dish for image recording on a flatbed digital scanner (Model 6300 C, Hewlett Packard). Images were digitized at 200 dpi resolutions. Scanned root images were processed by WR-RIPL, version 2.0

using the Sun Ultra computer in the Michigan State University RIPL (http://www.rootdig.css.msu.edu). Root length was calculated using an image resolution of 78.74 pixels per cm (for 200 dpi resolution only) by the image processing system. Surface area and volume were calculated using equations [1] and [2].

Soil subsamples were weighed at their field water contents and mineral N was extracted from field moist samples. Approximately twenty grams of moist soil were sampled from the one-half each of the two hydraulic core samples from each horizon sampled in each field plot, placed in a 250 ml Erlenmayer flask containing 50 ml of 1 N KCl extraction solution and shaken to equilibrium on a rotary shaker for one hour. Clear solutions were expressed by filtering the soil slurry through Whatman No.1 filter papers, folded and placed in funnels. Clear soil sample solutions were stored in 20 ml scintillation vials at 4°C until analyzed for NO_3 and NH_4 by the cadmium reduction method using a QuickChem Automated Ion Analyzer (Lachat Instruments, 6645 West Mill Road, Milwaukee, WI). Average concentration values of NO_3-N plus NH_4-N (mg g^{-1} oven dry soil) were combined with soil bulk density for each horizon, adjusted to air dry soil to calculate kg N per ha using the following equation.

$$\text{Kg N ha}^{-1} = \frac{(\text{mg N kg}^{-1}) \times (\text{b.d} \times 1000) \times (10000) \times (\text{thickness} / 100)}{1000000} \qquad [3]$$

b.d = Bulk density of soil horizon (t m^{-3}),

Thickness = Thickness of soil horizon (cm)

Statistical analysis

Plant and soil parameters were analyzed by a PROC-GLM (General Linear Models) procedure using Statistical Analysis System (SAS Institute, 1999, Cary, NC). SAS codes for ANOVA were generated by using code generator program (http://www.cas.vt.edu/schabenb). Average of two subsamples of soil N in each plot was determined and standard deviations of means were calculated for four field replications. Fishers LSD test was used to separate means of measurements. Correlation analyses was used to determine relationships between root, plant and soil parameters. Analyses were conducted separately for 1998 and 1999. All significant tests were set at Probability levels of at least 0.05.

RESULTS AND DISCUSSION

Soil nitrogen

Soil nitrogen contents in 1998 were higher in the A_p horizons when NT-F treatments had a rye cover crop. This trend was reversed in 1999 when fall through early spring precipitation was 38% less (Figure 2.1). Cover crops appeared to have a smaller affect on soil N contents in the A_p horizons of CT-F in 1998 (Figure 2.2). Lower fall through early spring precipitation and a better winter and early spring rye cover crop in 1999 lowered soil N contents in the A_p horizon from 50 kg N per ha to 25 to 30 kg N per ha regardless of soil tillage (Figures 2.1 and 2.2). Rye cover crops modified the distributions of N within the soil profiles of conventional tillage treatments (Figure 2.2) as more N accumulated in the Bt_2 and C_1 horizons when rye cover treatments were present during the wetter year in 1998, but these two deeper horizons as well as the shallower horizons contained lower N during the drier year in 1999.

Less N leaching from the A_p horizons of no rye treatments resulted in 1999 due to nearly 40% less precipitation during the fall through early spring compared to the same period of time in 1998 (Figures 2.1- 2.4).

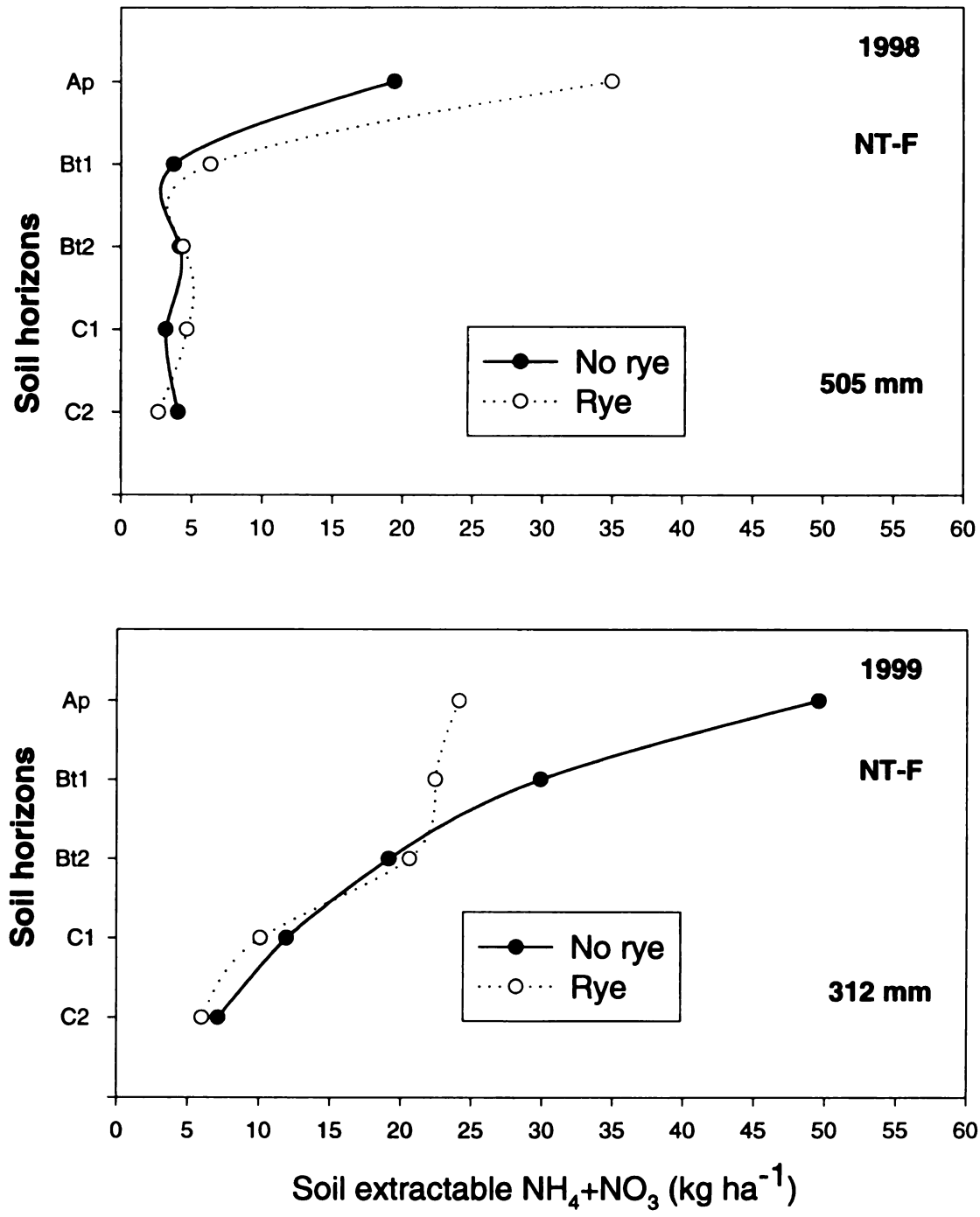


Figure 2. 1. Extractable soil mineral nitrogen within the profiles of no-tilled and N fertilized (NT-F) with rye cover and no cover crop plots of a Kalamazoo loam, at KBS Interactions sites, in May 20, 1998 and April 21, 1999, (n=4). Values of mm are precipitation for September-April of each year.

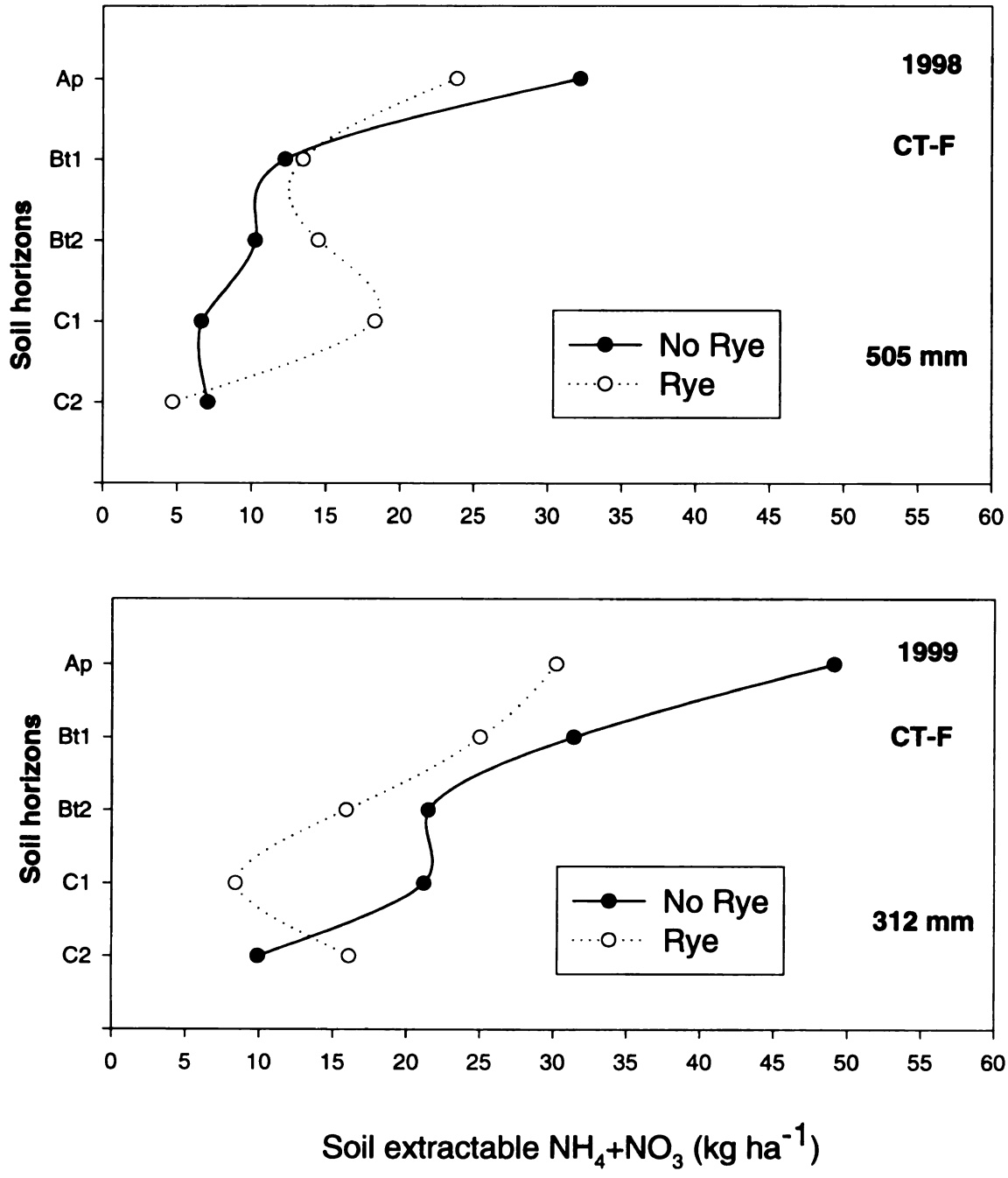


Figure 2. 2. Extractable soil mineral nitrogen within the profiles of conventionally tilled and N fertilized (CT-F) with rye cover and no cover crop plots of a Kalamazoo loam, at KBS Interactions sites, in May 20, 1998 and April 21, 1999, (n=4). Values of mm are precipitation for September-April of each year. (n=4).

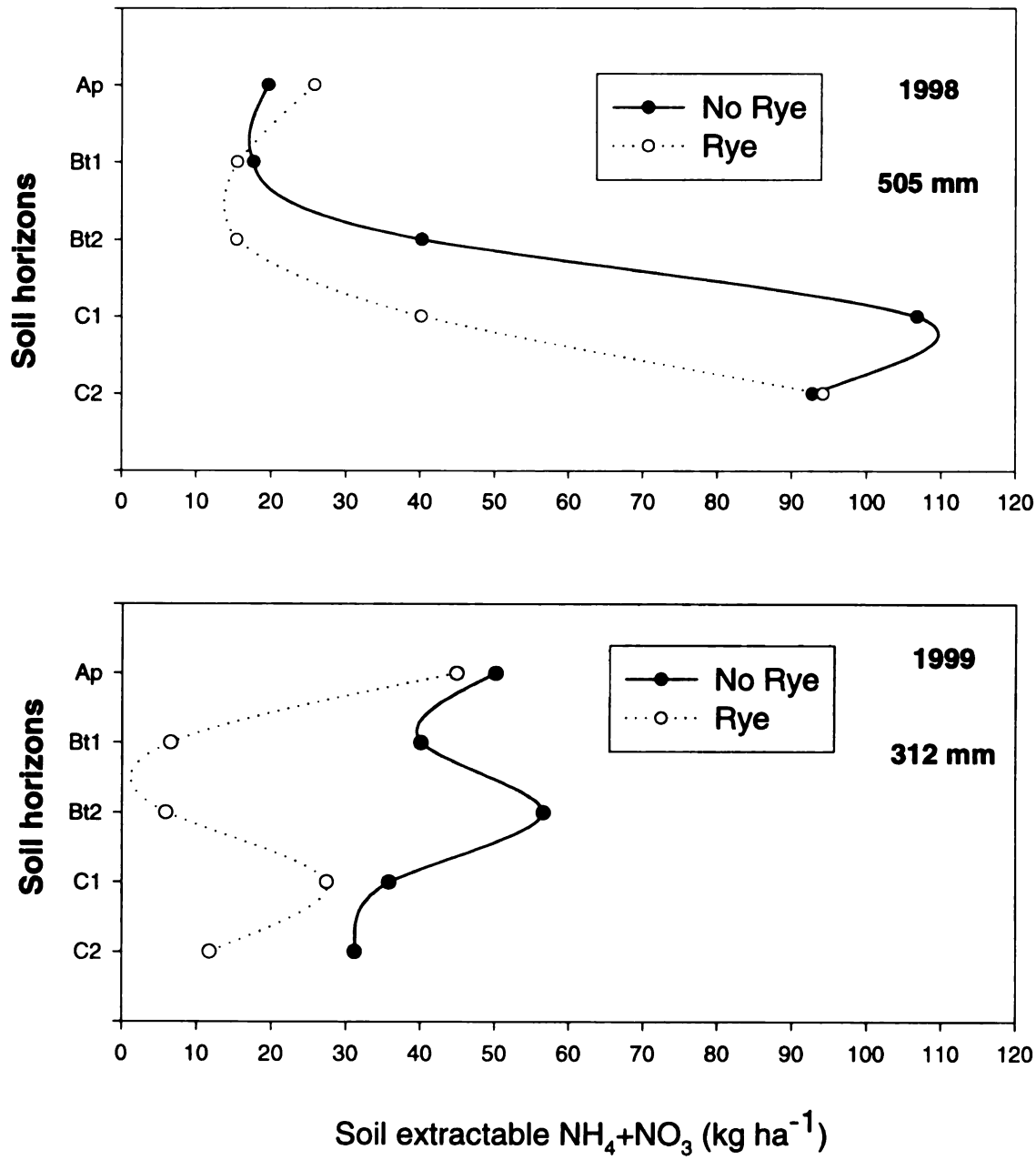


Figure 2. 3. Extractable soil mineral nitrogen within the profiles of a Kalamazoo loam in April 11, 1998 and April 29, 1999. Rye and no rye cover crop treatments were applied to the Microplots site at KBS (n=4). Values of mm are precipitation for September-April of each year.

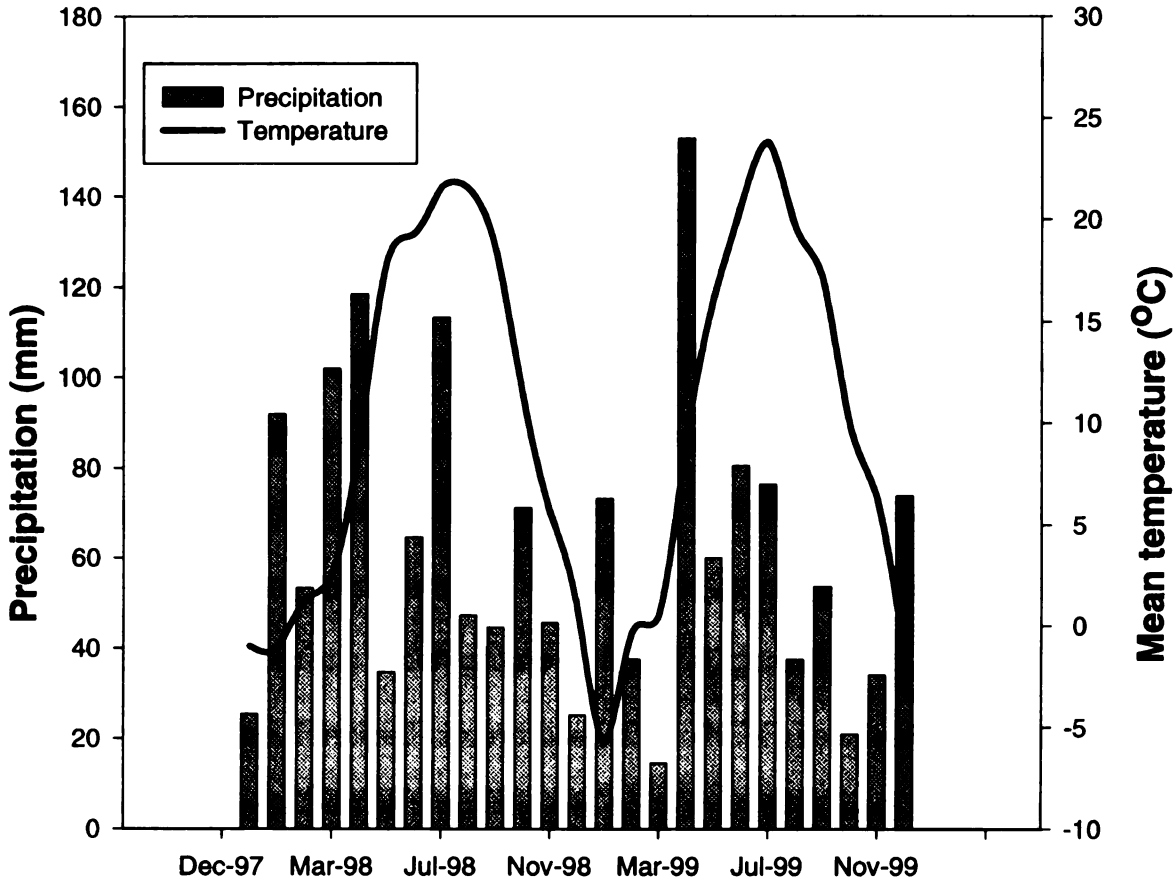


Figure 2.4. Precipitation and temperature recorded at the KBS LTER weather station from December 1997 to December 1999.

Absorption of soil N by the rye cover crop (Figures 2.6 and 2.7) together with plugging of some of the soil macropores by rye roots (Rasse, et al., 1999) appeared to reduce the adverse effects of precipitation on N leaching through soil profiles protected by cover crops. More soil inorganic N was retained within the soil profiles seeded to a fall rye cover in 1999 compared to spring-seeded rye cover in 1998. Spring seeding of rye in wet year resulted in leaching of inorganic N below the rooting zone of CT-F plots during the Fall of 1997 and Spring of1998. However in the absence of rye, leaching of inorganic N beyond the rooting zone of corn was much greater in 1999 (Figure 2.2).

Rye planted, fertilized and no-tilled plots (NT-F) retained 57% more N within the soil profile in April 1999 than in May 1998 (Figure 2.1). Rye planted, fertilized and conventionally tilled plots (CT-F) retained 28% more N within soil profile in April 1999 than in May 1998 (Figure 2.2).

Fall seeded rye cover removed 24 kg N/ha from the A_p horizon in 1999 (Figure 2.2). Less rainfall and infiltration retained larger gradients of soil N from A_p to C_2 horizons in the no rye cover treatments in 1999. However, more N was removed from the A_p horizon by cover crop and/or retained in the Bt horizons by the mechanical plugging of soil pores by living rye roots which invaded these soil depths.

By subtracting plant N plus soil inorganic N in April from total soil inorganic N in November, distributions of N within plant and soil could be calculated. The

unaccounted N was presumed lost by leaching. If mineralization of soil N is greater than the leaching (dry year), then there is retention of N in the soil.

The roots and shoots of rye cover crop, removed 25% of N (Figure 2.6A) from the soil profile and retained from 36.4 to 53.1 kg soil N ha^{-1} in conventionally tilled and from 28.0 to 40.7 kg soil N ha^{-1} in no-tilled plots in 1998 (Table 2.1).

Cover crop reduced soil loss of N by absorbing 53.1 kg soil N ha^{-1} from CT-F plots and 40.7 kg soil N ha^{-1} from NT-F plots in 1998 (Table 2.1). Residual N from Fall to next Spring was distributed as 11, 14, 41% among the rye root, shoot and soil respectively for conventionally tilled and fertilized plots (Figure 2.6 A). Consequently 34% of the soil N was lost from CT-F below the root zone by leaching. In the absence of cover crop leaching below the root zone was 66% (Figure 2.6 B) which was 138.6 kg soil N ha^{-1}.

Residual N of no-tilled and fertilized (NT-F) plots in Spring was distributed as 14, 22, 59% among the rye root, shoot and soil respectively (Figure 2.6 C). Nitrogen loss from these plots was 5% that was very low. In the absence of cover crop, loss of N by leaching below the rooting zone was 69% (Figure 2.6 D) equivalent of 78.7 kg soil N ha^{-1}(Table 2.1).

Nitrogen distribution was 11, 29, 54% among the rye root, shoot and soil respectively and the loss was 6% for conventionally tilled and non- fertilized plots (Figure 2.7 A). Plots with no cover crop lost 59% (Figure 2.7 B).of soil N equivalent of 53.9 kg soil N ha^{-1} (Table 2.1).

Residual N distribution was 9, 30 and 53% among the rye root, shoot and soil respectively and loss was 8% for no-tilled and non- fertilized plots (Figure 2.7 C). In the absence of rye cover crop leaching loss was 45% (Figure 2.7 D).of soil N which was 32.3 kg soil N ha^{-1} (Table 2.1).

N retention was greater than the N loss in a dry year (Figures 2.8 and 2.9) in both rye and no-rye cover cropped plots in April 1999 compared to May 1998.

Gain and the retention of soil N was greater under conventionally tilled plots in 1999. Rye planted and conventionally tilled plots retained more N than no cover cropped and conventionally tilled plots in 1999 (Figure 2.8 A and B). However no-tilled and rye planted plots with N fertilizers lost 10.9 kg residual N ha^{-1} in 1999 compared to no cover cropped plots (Table 2.2). The differences between retained soil N of cover cropped and no cover cropped plots of NT were not statistically significant in the absence of N fertilization (Figures 2.9 C and D).

Greater gain of N under CT plots in a dry year (1999) and greater N loss from CT plots in a wet year (1998) suggest that there is more N leaching potential for these plots if the weather conditions are suitable. Residual soil N in 1997 fall was twice as much greater than that in fall 1998. Previous alfalfa crop was spray killed in Spring of 1996 and N derived from mineralized alfalfa roots increased soil N pool from February 96 to January 98 (Figure 2.5). Due to greater residual N in the soil profile combined with wet fall, winter and spring, more N leached from the soil profile in 1998 than in 1999.

Fertilized, conventionally tilled and cover crop planted plots lost 29% more residual inorganic N than no tilled soil (Figures 2.6 A and C). Similar results

indicating greater NO_3 leaching from CT plots compared to NT plots have been reported. (Goss et al, 1993). Ploughing increased the loss by 21% compared to no till. In this research, tillage differences on NO_3 leaching were greater with fertilizer application than no fertilized treatments. Angle et al, (1993), reported that average NO_3 concentration below a depth of 30 cm for all treatments and all years under CT plot was greater than those under the no till plots. Consequently, despite the greater cumulative water drainage from non fertilized NT plots (Rasse, 1997, Weed and Kanwar, 1996), total amount of inorganic N leaching was lower than CT plots due to higher NO_3-N concentrations in CT leachates (Figure 2.5).

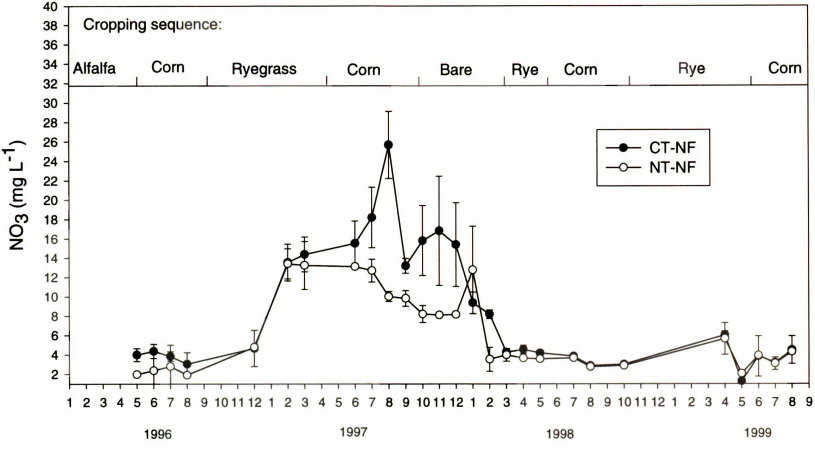
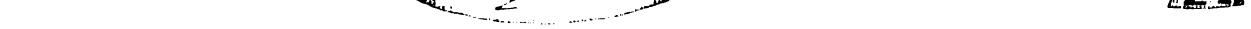


Figure 2. 5. NO_3 leaching from drainage waters of monolith lysimeters containing conventionally tilled (CT) and no tilled (NT) Kalamazoo loam without N fertilization since 1991, at the Interactions site, from May 1996 to August 1999. Statistical bars are standard deviations for n=2.



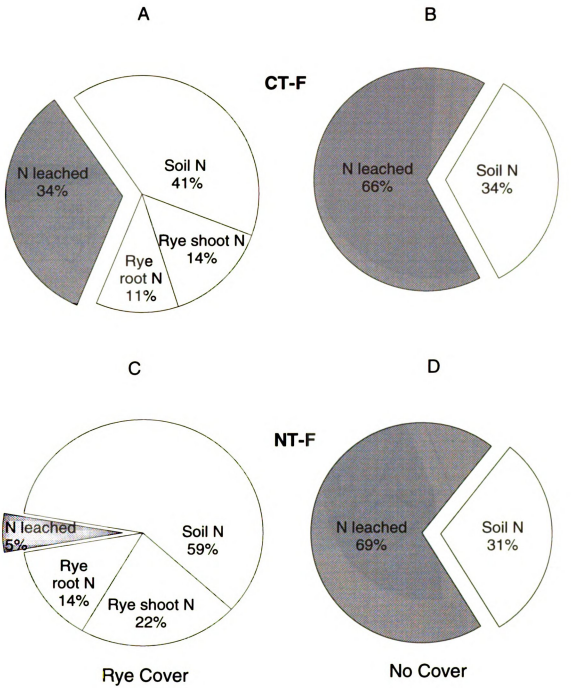


Figure 2.6. Distribution of inorganic N in rye cover and soil (0-150 cm) and leaching from a Kalamazoo loam soil in May 1998. (A) was conventionally tilled and N fertilized with rye cover; (B) was conventionally tilled and N fertilized with no rye cover; (C) was no tilled and N fertilized with rye cover; and (D) was no tilled and N fertilized with no rye cover at the interaction sites.

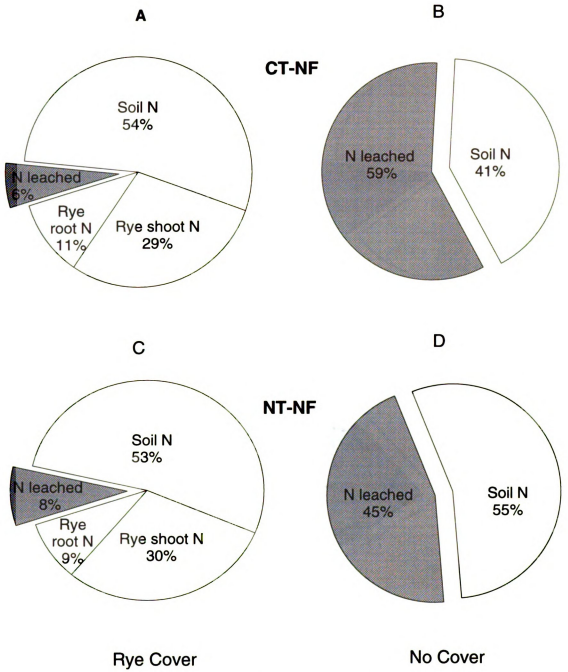


Figure 2.7. Distribution of inorganic N in rye cover and soil (0-150 cm) and leaching from a Kalamazoo loam soil in May 1998. (A) was conventionally tilled and no N fertilized with rye cover; (B) was conventionally tilled and no N fertilized with no rye cover; (C) was no tilled and no N fertilized with rye cover; and (D) was no tilled and no N fertilized with no rye cover at the Interaction sites.

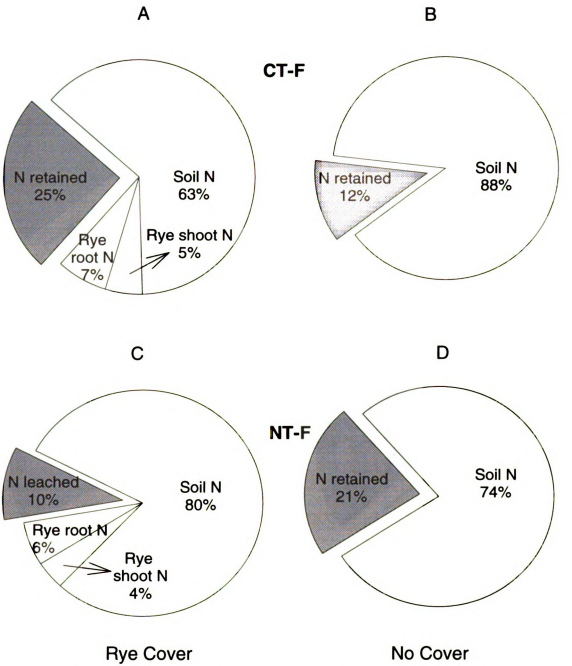


Figure 2.8. Distribution of inorganic N in rye cover and soil (0-150 cm) and retention or leaching from a Kalamazoo loam soil in April 1999.
(A) was conventionally tilled and N fertilized with rye cover;
(B) was conventionally tilled and N fertilized with no rye cover;
(C) was no tilled and N fertilized with rye cover; and
(D) was no tilled and N fertilized with no rye cover at the interaction sites.

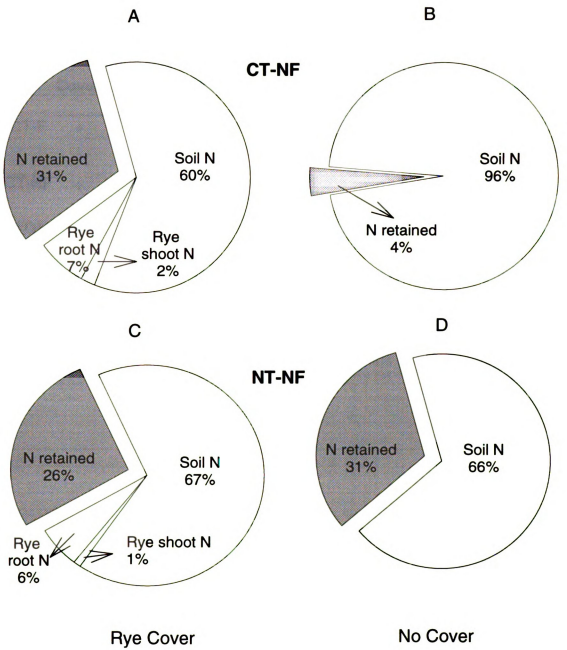


Figure 2.9. Distribution of inorganic N in rye cover and soil (0-150 cm) and retention or leaching from a Kalamazoo loam soil in April 1999.
(A) was conventionally tilled and no N fertilized with rye cover;
(B) was conventionally tilled and no N fertilized with no rye cover;
(C) was no tilled and no N fertilized with rye cover; and
(D) was no tilled and no N fertilized with no rye cover at the Interaction sites.

Table 2.1. Distribution and loss by leaching of inorganic N in rye cover and soil (0-150 cm) of a Kalamazoo loam at the Interactions sites in May 1998.

		Rye root		Rye shoot		Soil		Loss	
	Cover	N	SE†	N	SE	N	SE		SE
					kg ha^{-1}				
CT-F	+	23.2	0.8	29.9	2.5	84.5	28.8	71.4	32.0
	-	-	-	-	-	70.3	15.1	138.6	18.5
CT-NF	+	9.9	3.0	26.5	3.4	49.6	10.3	5.9	8.3
	-	-	-	-	-	38.0	21.0	53.9	39.3
NT-F	+	15.4	0.2	25.3	8.8	66.6	18.9	6.0	18.5
	-	-	-	-	-	34.6	4.0	78.7	7.2
NT-NF	+	6.2	1.7	21.8	4.0	37.7	9.0	5.8	8.0
	-	-	-	-	-	39.2	12.0	32.3	27.5

† SE is the standard errors of the means, n=4

Table 2.2. Distribution, loss or gain (in parentheses) of inorganic N in rye cover and soil (0-150 cm) of a Kalamazoo loam at the Interactions sites in April 1999.

	Cover	Rye root N	SE†	Rye shoot N	SE	Soil N	SE	Loss or gain	SE
		kg ha^{-1}							
CT-F	+	14.0	3.2	8.9	2.4	123.0	0.5	(48.6)	5.1
	-	-	-	-	-	133.5	46.5	(18.2)	40.2
CT-NF	+	13.0	0.2	3.5	0.2	110.1	38.9	(57.8)	32.5
	-	-	-	-	-	70.9	2.1	(2.6)	4.5
NT-F	+	6.0	0.9	4.1	1.0	83.4	10.5	10.9	15.1
	-	-	-	-	-	117.7	11.3	(31.7)	0.1
NT-NF	+	7.0	2.3	1.6	0.3	75.5	20.2	(84.3)	13.9
	-	-	-	-	-	104.2	7.3	(54.2)	12.2

† SE is the standard errors of the means, n=4.

Regardless of cover crop treatment, grain yield, stalk biomass and utilization of N by corn were significantly greater under CT treatment than NT treatment (Figure 2.10 and Tables 2.3 and 2.4) in 1998 and 1999. Therefore, residue return to the CT plots after corn harvest and associated N mineralization are higher than those in NT soil (McCarthy et al., 1995). Greater N gain in spring of a dry year may be due to more mineralization of residue and soil organic material from CT plots than NT plots. An additional explanation to why soil inorganic N leaching was lower under NT plots may be that denitrification and microbial immobilization of N is often higher under NT treatments (Angle et al., 1993, Meisinger et al., 1985, Rice and Smith, 1982). More water infiltration through NT plots (Rasse, 1997), may have kept soil profile wetter and created more anaerobic sites which enhances denitrification (Weed and Kanwar, 1996). However, we do not have the measurements of denitrification rates from CT and NT plots to support this explanation.

During the entire 2 yrs study, cover crop had greater influence on the amount of inorganic N lost below rooting zone of Kalamazoo loam soil. Low residual soil inorganic N following rye in a wet year was due mainly to nitrogen uptakes by rye roots and shoots which were 53.1 and 40.7 kg residual soil N ha^{-1} from CT-F and NT-F plots in 1998 respectively. Shipley et al., (1992) reported that cereal rye retained 48 kg N ha^{-1} of residual soil N when it was killed in mid April. Kessavalou and Walters (1999), observed similar uptakes by rye cover crop (42-48 kg N ha^{-1}). However in the absence of cover crop leaching losses from CT-F and NT-F plots were 138.6 and 78.7 kg residual soil N ha^{-1}. Therefore,

85.5 and 38 kg N ha^{-1} retained in the soil profile of CT-F and NT-F plots as a result of occupation and mechanical plugging of soil pores by rye roots. Reduction of inorganic soil N leaching under rye cover crop was observed by several investigators (Kuo et al., 1997, McCracken et al., 1994, Ditsch et al., 1993, Shipley et al., 1992). Dual spray applications of herbicide to Roundup-ready corn, planted directly into decomposing rye cover crops, resulted in the contribution of at least 28 kg N per ha (NT-NF) to the 1998 corn crop and reduced nitrogen losses to groundwater below the root zone by 26.5 to 72.7 kg N per ha during the year.

Table 2. 3. Cover crop modifications of total N and C in whole plant corn shoot responses to tillage and N fertilization of a Kalamazoo loam in July 1998, n=4.

Treatment	N	C	C:N	Total corn biomass
	%			kg ha^{-1}
Tillage				
CT	3.6a†	43.6a	12.5b	3766a
NT	2.8b	42.7a	16.3a	1677b
Fertilization				
F	3.5a	44.7a	12.5b	3220a
NF	2.8b	42.7b	16.3a	2223b
Cover				
Rye Cover	3.2a	43.2a	13.1b	2545b
No Rye cover	3.2a	44.2a	15.7a	2899a
No Rye cover				
CT-F	4.1a	43.9a	10.8d	5014a
CT-NF	3.3b	43.5a	13.2c	2786b
NT-F	3.0b	46.4a	15.4b	2357b
NT-NF	2.4c	42.9a	17.9a	1436b
Rye Cover				
CT-F	4.0a	44.7a	11.2b	3621a
CT-NF	3.0ab	42.5a	14.9ab	3643a
NT-F	3.0ab	43.8a	15.0ab	1886b
NT-NF	2.6b	41.8a	16.8a	1029b

† Columns (for each treatment), labeled with the different letters are significantly different at $P<0.05$ according to Fisher's LSD mean separation test.

Table 2. 4. Cover crop modifications of total N and C in whole plant corn shoot responses to tillage and N fertilization of a Kalamazoo loam in July 1999, n=4.

Treatment	N	C	C:N	Total corn biomass
	%			kg ha^{-1}
Tillage				
CT	1.3a†	43.6a	33.7b	5031a
NT	1.1b	42.7a	38.6a	3000b
Fertilization				
F	1.4a	43.4a	32.75b	4874a
NF	1.1b	42.8a	39.53a	3156b
Cover				
Rye Cover	1.2a	43.5a	36.3a	3703b
No Rye cover	1.2a	42.7a	36.0a	4328a
No Rye cover				
CT-F	1.7a	42.2a	25.4b	6582a
CT-NF	1.1b	42.4a	38.6a	3815b
NT-F	1.2b	43.8a	37.9a	4166b
NT-NF	1.0b	42.5a	42.0a	2750b
Rye Cover				
CT-F	1.4a	43.5ab	31.5a	5166a
CT-NF	1.1b	42.6b	39.0a	4562ab
NT-F	1.2ab	44.2a	36.2a	3583b
NT-NF	1.2b	43.8ab	38.5a	1500c

† Columns (for each treatment), labeled with the different letters are significantly different at $P<0.05$ according to Fisher's LSD mean separation test.

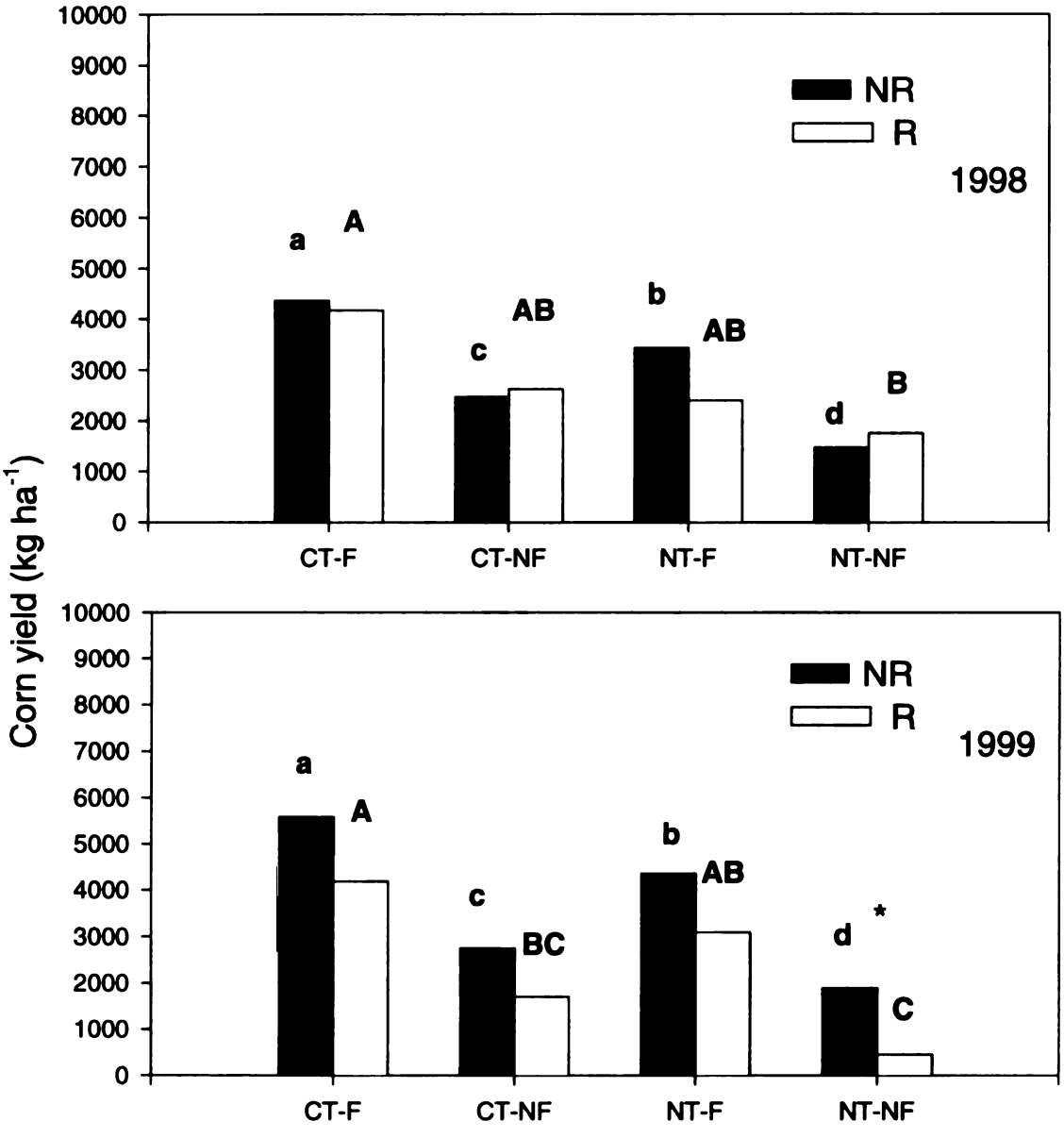


Figure 2.10. Corn grain yields at KBS Interactions sites in 1998 and 1999. CT and NT refer to conventional and no tillage, F and NF refer to 150 and 0 kg N fertilizer per ha. NR and R refer to no rye cover and rye cover crops.

Mean values followed by the different uppercase letter within rye cover crop treatment and different lowercase letter within no rye cover crop treatments are significantly different at $p<0.05$ according to Fisher's LSD mean separation test. Star (*) indicates the significant difference between the corn yield of rye vs. no rye cover crop plots ($P<0.05$).

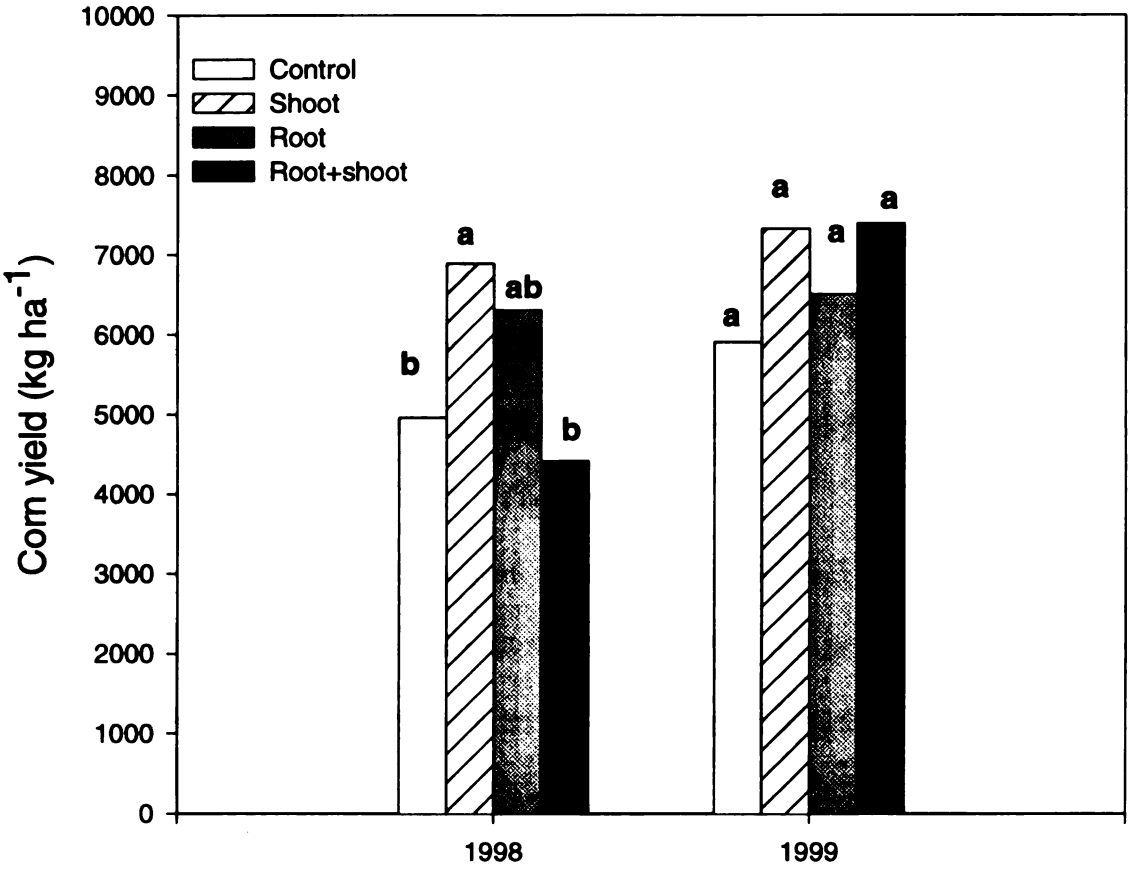


Figure 2. 11. Corn grain yields at KBS-LTER in main areas of microplots in 1998 and 1999. Mean values followed by the different letter within a same year and between treatments are significantly different at p< 0.05 according to Fisher's LSD mean separation test.

Cover crop roots

Most of the rye root widths (50-100%) were classified as Class 2 sized roots having 0.05 cm. Roots in Ap and Bt_1 horizons of the CT-F and NT-F treatments had more roots with larger diameters than those in below soil horizons (Table 2.5) and resulted with greater volume and surface area (Table 2.7). All of the rye roots in Microplots sites had diameter between 0.02 and 0.05 cm and were classified as Class 2 (Table 2.6).

Root surface area density was in the range of 1.15-5.88 m^2 m^{-3} for Ap horizons of Interactions and Microplots sites (Tables 2.7 and 2.8). This range was slightly lower than the one for cotton roots (approximately 7) reported by Brouder and Cassman (1990).

Negative correlations were observed between extractable soil inorganic N content (Table 2.9) and root length, volume and surface area in Ap horizons of all fertilized and non-fertilized treatments of Interactions sites ($p<0.05$). Similar negative relationships were also observed in Microplots sites (Table 2.10). Supporting results were reported by Upendra et al.,(1998). They found negative correlations between cover crop minirhizotron root counts and soil nitrate concentrations in Fall ($r=-0.55$) and in Winter ($r=-0.51$) at 0-30 cm soil depths. This negative correlation appeared to be due to uptake of N from the Ap horizon by the rye roots. Since inorganic soil N and roots were extracted from the same soil core sample, larger root numbers could be correlated with depletion of soil N in primarily in the Ap horizon.

Table 2.5. Percentage of root lengths in individual root width classes in A_p, B_{t1}, B_{t2}, C1 and C2 horizons of conventionally tilled and fertilized (CT-F), conventionally tilled and non-fertilized (CT-NF), no tilled and fertilized (NT-F) and no tilled and non-fertilized, rye cover planted, treatments in a Kalamazoo loam soil at KBS-Interactions sites on May 20, 1998.(SE=standard errors, n=4)

		Root width classes									
		Class 1 0.02 cm		Class 2 0.05 cm		Class 3 0.09 cm		Class 4 0.14 cm		Class 5 0.21 cm	
Treatment	Horizon	Average	SE	Average	SE	Average	SE	Average	SE	Average	SE
CT-F	Ap	3.9	3.3	73.9	3.3	17.4	3.7	4.9	2.4	0.8	0.7
CT-F	Bt1	3.5	3.1	66.9	26.7	28.1	22.3	1.5	1.3	0.6	0.6
CT-F	Bt2	0.0	0.0	99.3	0.5	0.7	0.5	0.0	0.0	0.0	0.0
CT-F	C1	0.0	0.0	99.1	0.7	0.9	0.7	0.0	0.0	0.0	0.0
CT-F	C2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CT-NF	Ap	0.0	0.0	98.9	0.8	1.1	0.8	0.0	0.0	0.0	0.0
CT-NF	Bt1	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CT-NF	Bt2	0.1	0.1	50.0	35.4	49.9	35.3	0.0	0.0	0.0	0.0
CT-NF	C1	0.0	0.0	98.3	1.5	1.7	1.5	0.0	0.0	0.0	0.0
CT-NF	C2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NT-F	Ap	4.6	4.0	89.5	9.1	2.7	2.4	2.2	1.9	1.0	0.9
NT-F	Bt1	4.3	4.3	86.0	11.6	7.7	5.5	1.3	1.3	0.7	0.7
NT-F	Bt2	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NT-F	C1	0.0	0.0	99.4	0.4	0.6	0.4	0.0	0.0	0.0	0.0
NT-F	C2	62.7	0.0	19.6	0.0	3.2	0.0	4.6	0.0	9.9	0.0
NT-NF	Ap	2.5	2.2	70.0	17.5	18.6	11.7	6.6	5.2	2.3	1.8
NT-NF	Bt1	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NT-NF	Bt2	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NT-NF	C1	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NT-NF	C2	48.5	0.0	51.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2.6. Percentage of root lengths in individual root width classes in Ap, Bt_1, Bt_2, C_1 and C_2 horizons of N fertilized and rye cover planted treatment in a Kalamazoo loam at KBS-Microplots sites on April 11, 1998. (SE=standard errors, n=4)

	Root width classes									
	Class 1		Class 2		Class 3		Class 4		Class 5	
	0.02 cm		0.05 cm		0.09 cm		0.14 cm		0.21 cm	
Horizon	Average	SE	Average	SE	Average	SE	Average	SE	Average	SE
Ap	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bt1	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bt2	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C1	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C2	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2.7. Root length density, volume density and surface area density in Ap, Bt_1, Bt_2, C_1 and C_2 horizons of conventionally tilled and fertilized (CT-F), conventionally tilled and non-fertilized (CT-NF), no tilled and fertilized (NT-F) and no tilled and non-fertilized (NT-NF), rye cover planted, treatments in a Kalamazoo loam soil at KBS Interactions sites on May 20, 1998. (SE= standard errors, n=4)

		Root length density		Root volume density		Root surface area density	
		km m^{-3}		m^3 m^{-3}		m^2m^{-3}	
Treatments	Horizon	Average	SE	Average	SE	Average	SE
CT-F	Ap	2.24	1.46	1.93E-05	1.42E-05	5.88	3.95
CT-F	Bt1	1.58	0.82	1.63E-05	1.25E-05	5.08	3.34
CT-F	Bt2	1.03	0.22	2.95E-06	5.95E-07	1.95	0.41
CT-F	C1	0.66	0.32	1.96E-06	9.64E-07	1.27	0.62
CT-NF	Ap	1.09	0.39	3.13E-06	1.07E-06	2.07	0.73
CT-NF	Bt1	0.41	0.04	1.15E-06	1.09E-07	0.77	0.07
CT-NF	Bt2	0.53	0.27	5.34E-06	3.50E-06	1.85	1.12
CT-NF	C1	0.18	0.11	5.75E-07	3.68E-07	0.36	0.22
NT-F	Ap	0.79	0.18	3.59E-06	1.20E-06	1.62	0.34
NT-F	Bt1	0.57	0.17	3.24E-06	1.90E-06	1.27	0.47
NT-F	Bt2	0.12	0.02	3.47E-07	6.46E-08	0.23	0.04
NT-F	C1	0.88	0.08	2.55E-06	2.52E-07	1.68	0.15
NT-NF	Ap	1.11	0.66	8.56E-06	3.10E-06	3.06	0.98
NT-NF	Bt1	0.29	0.08	8.23E-07	2.34E-07	0.55	0.16
NT-NF	Bt2	0.71	0.37	2.00E-06	1.05E-06	1.33	0.70
NT-NF	C1	0.23	0.11	6.56E-07	3.08E-07	0.44	0.21

Table 2.8. Root length density, volume density and surface area density in Ap, Bt_1, Bt_2, C_1 and C_2 horizons of N fertilized and rye cover planted treatment in a Kalamazoo loam at KBS-Microplots sites on April 11, 1998. (SE=standard errors, n=4)

	Root length density km m^{-3}		Root volume density m^3 m^{-3}		Root surface area density m^2m^{-3}	
Horizon	**Average**	**SE**	**Average**	**SE**	**Average**	**SE**
Ap	0.61	0.06	1.73E-06	1.80E-07	1.15	0.12
Bt1	1.33	0.78	3.72E-06	2.16E-06	2.48	1.44
Bt2	0.64	0.44	2.02E-06	1.17E-06	1.35	0.78
C2	0.14	0.10	4.06E-07	2.71E-07	0.27	0.18

Table 2.9. Correlation coefficients (r) between extractable inorganic N content and rye root length, volume and surface area in Ap, Bt_1, Bt_2, C_1 and C_2 horizons of N fertilized (N) and non-fertilized (NF) treatments of a Kalamazoo loam soil at KBS-Interactions sites in May 20, 1998, n=8 (p=0.05).

N Fertilized	Length	Volume	Surface area
Soil horizons	m ha^{-1}	m^3 ha^{-1}	m^2 ha^{-1}
A_P	-0.63	-0.67	-0.70
Bt_1	0.95	0.87	0.93
Bt_2	0.84	0.62	0.61
C_1	0.21	0.18	0.20
C_2	NA	NA	NA

Non- fertilized	Length	Volume	Surface area
Soil horizons	m ha^{-1}	m^3 ha^{-1}	m^2 ha^{-1}
A_P	-0.27	-0.78	-0.48
Bt_1	0.74	0.31	0.18
Bt_2	0.09	-0.42	-0.19
C_1	0.28	0.37	0.31
C_2	NA	NA	NA

Table 2.10. Correlation coefficients (r) between extractable inorganic N content and rye root length, volume and surface area in Ap, Bt_1, Bt_2, C_1 and C_2 horizons of N fertilized and rye cover planted treatment a Kalamazoo loam soil at KBS-Microplots sites in April 11, 1998, n=8 (p=0.05).

N Fertilized	Length	Volume	Surface area
	$m\ ha^{-1}$	$m^3\ ha^{-1}$	$m^2\ ha^{-1}$
A_P	-0.76	-0.63	-0.63
Bt_1	0.95	0.73	0.98
Bt_2	1.00	1.00	1.00
C_1	NA	NA	NA
C_2	NA	NA	NA

In contrast, positive relationships were observed between extractable soil inorganic N content and root length, volume and surface area in Bt_1 and Bt_2 horizons of fertilized treatments at both of the Interaction and Microplots sites (Tables 2.9 and 2.10). The reason for a negative correlations in Ap horizon and positive correlations in Bt_1 could be the different residence times of rye roots in these horizons. For example, root residence time in Ap horizon was much longer than those in deeper horizons resulting in more N uptake by roots from this horizon. Upendra et al.,(1998) reported that rye had much more greater root density in early growing season than in April in surface soil horizon. Therefore root length density could be longer in Ap horizon before April and May samplings and uptake of N by this roots reduced inorganic N in Ap horizon. Nitrogen uptake by rye roots in the Ap horizon of CT-F treatments was 27 ($\pm$5) mg N/m^2root/day and from Bt_1 horizon was 9 ($\pm$6) mg N/m^2root/day. Nitrogen uptake by rye root from Ap horizon of NT-F treatment was 8 ($\pm$1.4) mgN/m^2root/day and from Bt_1 horizon was 3 ($\pm$1.6) mgN/m^2root/day. Therefore, the negative correlations between inorganic N and surface areas of roots in Ap horizons were due to the more efficient N uptake by rye roots in this horizon. The reasons for positive correlations in Bt horizons (Tables 2.9 and 2.10) appears to be due to the accumulations of N that leached from primarily the Ap horizon and occupation of this N rich horizon by rye roots. Similar root surface areas between the Ap and Bt_1 horizons for the N fertilized tillage treatments at the Interactions site (Table

2.9) and microplot site (Table 2.10) further suggest N-stimulation of root growth and greater plant root uptake by the higher N treatments. Plugging of soil pores by these roots can be another reason for greater root and greater N content relation in this horizon. We previously reported that in the absence of cover crops, leaching losses from CT-F and NT-F treatments were 138.6 and 78.7 kg ha^{-1} (Table 2.1). Therefore 85.5 and 38 kg N ha^{-1} appeared to have been retained by soil due to plugging of soil pores by rye roots.

Rye roots absorbed 18.5 kg N ha^{-1} from 0-150 cm soil depth of Microplots in 1998. Absorption of soil N by rye roots was 23.2 kg N ha^{-1} (CT-F) where soil N content was 252 kg N ha^{-1}. Absorption of soil N by roots were 14.0 kg ha^{-1} in 1999 and soil N content was 115 kg N $ha^{-1}$from 0-150 cm soil depth. Rye roots and shoots reduced N leaching by 67.2 kg N ha^{-1} from the CT-F plots compared to no cover cropped plots in 1998 (Table 2.1). Residual soil N uptake by rye roots were similar to rye shoots however root contribution of N to the succeeding corn plant and soil N pool was greater than those by shoots (Kavdir, 2000-Chapter 4). Alfalfa root contributions to soil N pool was reported by Rasse et al.,(1999). Alfalfa shoot mulch contributed little to increases in soil N pools, while crowns and roots contributed larger quantities to the soil N pool. The positive correlation (R^2=0.55) was observed between total MR root length and rye shoot biomass in Spring 1999 (Figure 2.12). These results also suggest that increased root surface area and associated uptake of soil N by rye resulted in greater production of rye shoot biomass.

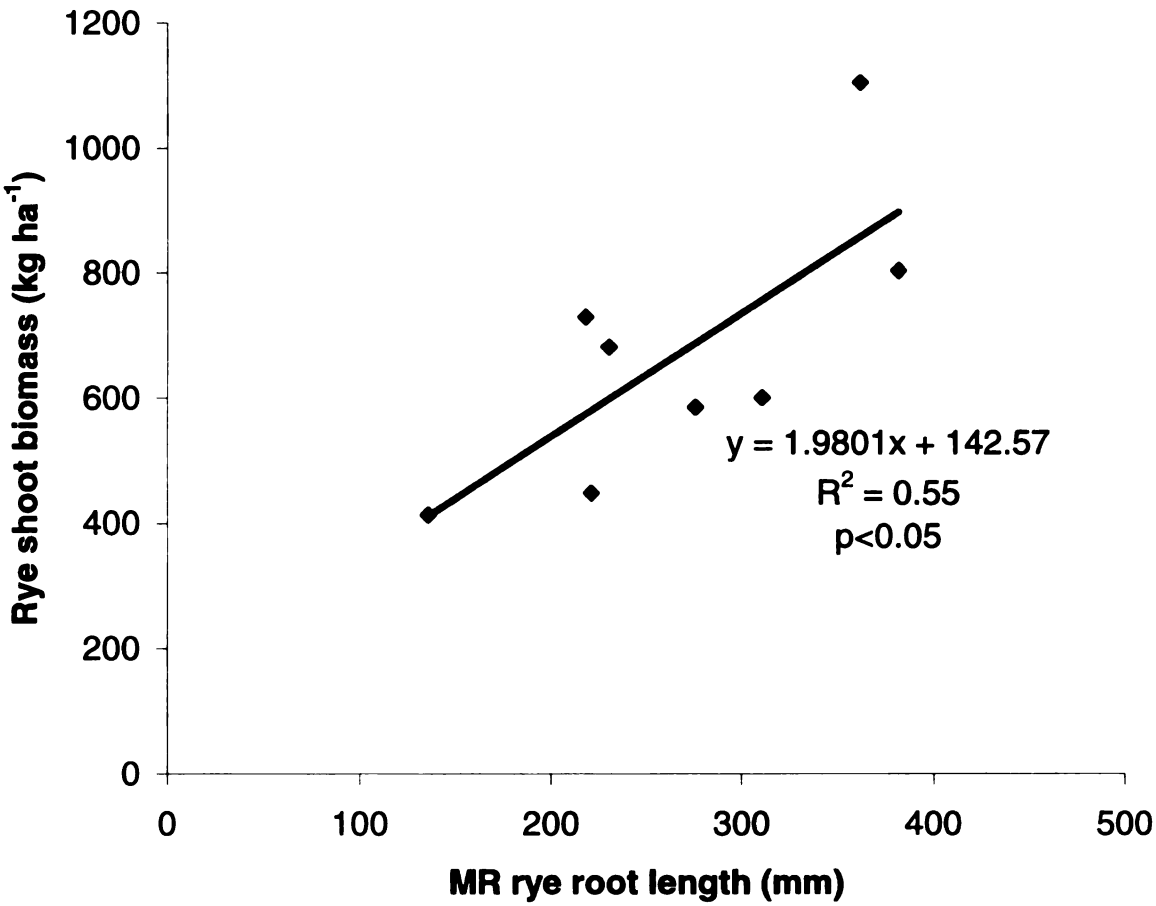


Figure 2.12. Relationship between rye shoot biomass and nondestructive minirhizotron evaluations of manually counted rye root lengths in 0-106 cm depths of a Kalamazoo loam in Spring, 1999 at KBS Microplots, n=16.

In a summary, rye cover crop roots absorbed N mostly from Ap horizon and reduced N leaching by immobilizing N in their shoots and roots. Root length density in Ap horizons of CT-F and CT-NF and those of NT-F and NT-NF were not significantly different. However they were significantly different in Bt_1 horizons of CT-F and NT-F treatments. Root surface area density was greater in Ap horizon of NT-NF treatment than those of NT-F treatment. Nitrogen source of non fertilized treatments are limited with plant root and shoot residues and SOM which are greater in Ap horizon of soil profile. Therefore N limitation in deeper soil horizons were resulted with greater root length and surface area in Ap horizons of NT-NF treatments than Bt horizons (Table 2.7). Root surface area density was not significantly different in Ap horizon of CT-NF than those of CT-F treatments (Table 2.7). Root surface area density was greater in Bt_1 horizons of CT-F treatment than those of CT-NF treatment and greater in NT-F treatment than those of NT-NF treatment. Greater root length and surface area density observed in Bt_1 horizons of fertilized plots than those in non fertilized plots due to more inorganic N content of this horizon. Greater N content in Bt_1 horizon of N fertilized treatments compared to non-fertilized treatments resulted in greater root penetration and positive linear correlation in this horizon. Therefore growing cover crop and keeping active roots in the soil between two successive cropping can reduce N leaching due to N utilization by cover crop roots and mechanical plugging of pores by these roots in upper soil horizons. Retained N in soil profile

together with N released from cover crop residues increases N utilization by the succeeding cash crop.

Rye biomass and nitrogen

Nitrogen fertilization increased rye biomass in 1999 ($P<0.05$). Rye shoot N uptake averaged 22 to 30 kg ha^{-1} in 1998 and 10 to 16 kg ha^{-1} in 1999. The C:N ratio of the rye shoot residue was found to be mostly dependent on the time of killing and decomposition rate. In the spring of 1998 (Table 2.11), relatively late rye killing and corn planting date resulted in more rye cover crop growth than 1999. Early killing of rye resulted in a narrower C:N ratio. C:N ranged from 10 to 14 in 1999 (Table 2.12). However, total biomass was smaller than that of later killed rye in 1998 (Table 2.11). It was suggested that small grain cereals should be killed when their C:N ratios are smaller than 30:1 (Reeves, 1994). However, in practice they are killed when their C:N ratio are over 30:1. This ratio results in an immobilization of N during the cropping season (Doran and Smith, 1991). In this study C:N ratios of rye were smaller than 30:1 at the time of desiccation in both years and resulted in early N availability for succeeding corn plant (Chapter 4). Other researchers also reported that lower C:N ratio of rye at the time of herbicide desiccation increased N mineralization (Kessavalou and Walters, 1999, and Kuo et al., 1997).

Table 2.11. Dry biomass, N, C and C:N contents of rye in conventional tillage (CT) and no tillage (NT) plots with nitrogen fertilization (F) and with no fertilization applied (NF) plots sampled in May 15, 1998 at Interactions sites, n=4.

05/15/1998								
Treatments	**Biomass**	**SD**	**N**	**SD**	**C**	**SD**	**C:N**	**SD**
	kg ha^{-1}		**%**		**%**			
CT-F	1221	473	2.6	0.5	42.7	0.8	17.1	4.0
CT-NF	985	222	2.7	0.4	43.2	0.6	16.3	2.5
NT-F	1271	875	2.0	0.1	42.1	0.5	21.1	1.2
NT-NF	1314	346	1.7	0.3	41.9	0.3	26.1	5.2

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Table 2.12. Dry biomass, N, C and C:N contents of rye in conventional tillage (CT) and no tillage(NT) plots with nitrogen fertilization (F) and with no fertilization applied (NF) plots sampled in April 19,1999 at Interactions sites, n=4.

04/19/1999								
Treatments	**Biomass**	**SD**	**N**	**SD**	**C**	**SD**	**C:N**	**SD**
	kg ha^{-1}		**%**		**%**			
CT-F	339	168	2.7	0.5	26.4	2.4	10.0	1.6
CT-NF	180	32	2.0	0.2	26.3	1.9	13.4	1.2
NT-F	186	84	2.2	0.4	27.7	1.4	13.0	1.6
NT-NF	79	33	2.0	0.1	28.2	0.6	13.9	0.8

Corn yield and nitrogen

Corn biomass and associated N concentrations increased on the CT-F treatments by 58% (no rye cover) and 44% (rye cover) compared to NT-F treatments in July 1999 (Table 2. 4). The reasons for the lower N uptake by corn in NT treatments can be the immobilization of fertilizer N by microbial biomass during decomposition of cover crop residue in NT plots and/or more NO_3 leaching from NT plots. Lower corn uptake of N should not have resulted from NO_3 leaching from the NT plots as field suction lysimeter data showed greater NO_3 leaching from CT plots than NT plots. NO_3 concentrations of leachate samples moving into the Bt_2 horizon averaged 37 mg L^{-1} in CT-F plots and 26 mg L^{-1} in NT-F plots in July, 1999. Large monolith lysimeter data also confirmed that CT plots lost more NO_3 by leaching from the soil profile (Rasse, 1997 and Figure 2.5). Another reasons for the greater N uptake by corn in CT treatments can be the aggregate breakdown by tillage. Nitrogen in the center of the aggregates becomes more available for plant uptake when aggregates are broken (Kavdir, 2000-Chapter 3).

It has been shown that microbial biomass C was greater when residues incorporated into the soil. However, microbial biomass N tended to be greater in soil with surface residues (Hubbard and Jordan, 1996). N immobilization by microbial biomass in NT treatments where residues placed on the soil surface may have caused less soil N uptake by corn plants in July compared to those in

CT treatments. Accumulations of corn biomass early in the growing season resulted in higher grain yields.

Grain yields of CT-F plots were 28% greater than the grain yields of NT-F plots in the absence of cover crop. In the presence of cover crop, corn grain yields of CT-F plots were 35% greater than the grain yields of NT-F plots in 1999 (Figure 2.10).

Grain yields of corn increased with N fertilization. Corn yields in rye planted plots increased by 52% in CT and 224% in NT plots due to the application of N fertilizer. In the absence of rye cover crop, grain yields increased by 76% and 132% in CT-F and NT-F plots respectively due to N fertilizer in 1998 (Figure 2. 10). N fertilization resulted in 103% and 584% increments in yield in 1999 within no cover crop planted and 145% and 524% yield increments in rye planted plots of CT-F and NT-F respectively.

Presence of rye in all plots did not significantly increased or decreased grain yield in both years. However, a direct linear correlation ($P<0.05$) between rye N content and grain yield ($R^2=0.75$ in 1998 and $R^2=0.75$ in 1999) was observed for all non-fertilized and rye planted treatments.

Grain yields in Microplots were significantly different between treatments in 1998 (Figure 2. 11). However, grain yields of rye planted plots of Microplots were 98% greater than those in Interactions plots in 1998 and 49% greater than those in Interactions plots in 1999. In the absence of cover crop treatment, grain yield of Microplots were 70% and 100% greater than the grain yields of rye planted NT-F plots of Interactions sites in 1998 and 1999 respectively. Killling time of rye

was different between these two sites. Rye was killed before corn planting in Microplots and rye was killed at the same time with corn planting in Interactions sites. Therefore, one of the reasons for yield differences can be different time of killing rye cover crops in Microplots and Interactions sites. However, grain yields of no rye planted treatments of Microplots were also different than those in Interactions sites . Also, other factors, such as slightly different seedling rate, differences in depths of soil horizons and the length of no tillage (12 yrs. In Interactions sites) treatment could have been effective on the yield.

Tillage and fertilization significantly increased grain yield in both years. Long term NT treatments of Interactions sites had lower grain yield than CT treatments. NT treatments had also lower corn yield than CT treatments in previous years (Rasse ,1997) at Interactions sites. Overall cover crop treatment did not significantly change corn yield except NT-NF treatment in 1999 which had lower yield than no cover cropped NT-NF treatment.

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CHAPTER 3

SOIL AGGREGATE SEQUESTRATION OF COVER CROP ROOT AND SHOOT RESIDUE NITROGEN

ABSTRACT

Rye (*Secale cereale L.*) roots and shoots release C and N compounds *in situ* during their decomposition. Plant deposition of N by rye roots and shoots onto soil aggregates was determined by labeling rye shoots with stable N isotope during rye cover cropping of corn agroecosystems. Rye plants were labeled with foliar applications of solutions containing 99% atom $(^{15}NH_4)_2SO_4$. Isotopic enrichment of soil aggregates ranging from 2.0 - 4.0, 4.0 - 6.3 and 6.3 - 9.5 mm across was determined following plant residue applications. Concentric layers of aggregates were removed from each aggregate by newly designed meso soil aggregate erosion (SAE) chambers.

Significant correlations were observed between changes in ratios of N concentrations in external layer/N concentrations in internal regions of aggregates 6.3-9.5 mm across and corn biomass production in 1999 (r^2=0.88 for no cover crop and r^2=0.71 for rye cover crop treatments). Some of the N in the external layers of soil aggregates were utilized by corn roots and/or diffused to the interior regions of aggregates.

Non-uniform distributions of total N and recently derived rye N in soil macroaggregates, across time, suggested that the formations and functions of macroaggregates are very dynamics processes. Rye roots contributed as much

N as rye shoots to the soil N pool. Therefore maintaining active plant root in the soil and keeping N on the surfaces of macroaggregates are the best management systems for maximizing soil N availability and reducing N leaching.

INTRODUCTION

Cover crops used to reduce leaching of NO_3 (Ditsch et al., 1993, McCracken et al., 1994) also contribute to the improvement of soil organic matter through the addition of residues in the early spring and throughout the summer. Microbes rapidly deplete decomposing plant residues of most sugars, amino sugars, organic acids, starches, and simple proteins (Paul and Clark, 1996). As decomposition continues, hemicelluloses, fats, waxes, and lignin are broken down into more consumable compounds (Killham,1994). As rye matures, the ratio of resistant to non-resistant materials increases, as does the C : N ratio in the plant. These changes in plant composition affect the residence times of C and N compounds adhering to the soil matrix.

Living rye roots, decomposition and by-products associated with the rye root and shoot residues are effective contributors to soil nutrient cycling and aggregate formation and stabilization. Kladivko (1994) reported that microbial decomposition of fresh organic material produced polysaccharides and other compounds that became the main contributors to the soil aggregate stabilization. Numerous studies have been reported on the formation, stabilization, and effect of different soil and crop management systems on soil aggregation (Wood et al., 1991, Roberson et al., 1995). However, there is little information on the location of recently decomposed plant residues within soil aggregates (Angers et al., 1997). Soil aggregation appears to improve when cover crops are added to cash crop rotations (Dormaar and Lindwall, 1989, and Angers et al.,1992). Plant roots

and shoot residues, wetting-drying cycles, soil organisms and soil texture control formation and stability of soil aggregates (Oades, 1993).

Growth of plant roots and development of soil aggregates conversely affect each other. Roots preferentially grow in the cracks and planes of weakness between aggregates rather than through aggregate interiors. Soil structure stability and associated mechanical impedance also impact root elongation rates, degree of contact at the soil-root interface as well as uptake of immobile nutrients (Whiteley and Dexter, 1983). The root systems of grasses are extensive and their position is generally inter-aggregate (Allison, 1973). Clay illuviation, preferential movement of water, weathering of clay and preferential growth of roots can change the compositions of aggregate surfaces (Smucker et al., 1997, Whiteley and Dexter, 1983, Wilcke and Kaupenjohann, 1998). Whiteley and Dexter (1983) reported that even when the soil was near saturation with a low penetrometer resistance, ped surfaces became a barrier to root penetration.

Sierra and Renault, (1996) reported that centers of aggregates contained less oxygen than the aggregate surfaces. Oxygen concentrations in interior decreased in large aggregates (Sextone et al., 1985, Hojberg et al., 1994). Aerobic respiration potential was reported to be greater near the surfaces of aggregates (Sierra and Renault, 1996). Therefore, it was assumed that oxygen gradients most likely control microbial activities, associated SOM decomposition, C and N accumulation in the soil aggregates. Contrasting C concentrations within interior and surface regions of aggregates were reported by Santos, (1998) and Smucker et al., (1997).

Living roots influence the chemical and biological properties of rhizosphere soil (Fisher et al., 1989). Rhizosphere effects are greater on the surfaces of the aggregates since roots are preferentially growing around the aggregate surfaces. Living roots can change pH, redox potential, water and nutrient content of the rhizosphere. They may create rapid wetting-drying cycles that enhance SOM degradation (Bottner, 1985). They may induce microbial activity and increase SOM decomposition (Cheng and Coleman, 1990). Roots control the concentrations and fluxes of soil N by absorbing soil water and soluble N compounds (Harper, 1995 and Frensch, 1996). Released N *in situ,* from decomposing plant roots and shoots contribute to stabilizing soil aggregation processes (Oades, 1993). Dead roots act as a readily decomposable SOM and cause increased oxygen consumption in rhizosphere (Fisher et al., 1989). Rhizodeposition, loss of organic materials from the roots, modifies rhizosphere soil (Mary et al., 1993, Ehrenfeld et al., 1997, Qian et al., 1997, Texier and Billes 1990, Jensen, 1996). Root exudates modify the solubility, sorption and transport of ions to the root surface, affecting the microbial activity. Rhizodeposition materials are water soluble exudates: sugars, aminoacids, organic acids, hormones, vitamins, water insoluble materials, cell walls, dead roots and mucilage (Cheng et al., 1993, Jensen, 1996). Nitrogen is deposited in the rhizosphere as NH_4, NO_3, and root debris. Janzen (1990) and Janzen and Bruinsma (1993) reported up to 20% of total plant N could be deposited to the rhizosphere of wheat plants. The amount of N deposited from pea residue was 48% of belowground N and from barley was 71% of total belowground N at

maturity (Jensen, 1996). It is assumed that, some of the extracted plant available N forms and mineralized N from rhizodeposits are reabsorbed by the plant. Janzen (1990) reported that the N rhizodeposits were usually labile but they become more recalcintrant with increased plant age.

Recent studies showed that soil aggregates develop by adding concentric layers of cations, carbon (Santos et al., 1997, Horn 1990, Smucker et al. 1997) and heavy metals (Wilcke and Amelung,1996). Short term effects of cropping on soil organic matter and associated rhizodeposition can be determined more quickly when concentric layers are removed from soil aggregates. Kay et al., (1988) did not find any changes in C and N contents of soil in short term. However, Angers and Mehuys (1989) found that 2 yrs of alfalfa and barley resulted in 15-25% higher carbohydrate contents compared to fallow or corn and 46–83% more carbohydrates compared to fallow treatment (Angers and Mehuys, 1990). Six weeks after planting ryegrass in a greenhouse potted study (Santos, 1998) showed exterior layers of soil aggregates contained 20% newly deposited C while interior regions contained only 8% new C_3-C. Therefore, under field cover crop conditions, it is suggested that recently derived rye cover crop shoot and root nitrogen could be deposited at greater concentrations on the surfaces of soil aggregates than interiors. To understand cover crop contributions of N to successive plant uptake and soil aggregation processes, sources and specific locations of N must be identified within soil aggregates. In this research, the contributions of roots and shoots by rye cover crop plants on soil N pool were measured separately. ^{15}N stable isotopes have been used in soil-plant systems

to investigate nitrogen transformations (Davidson et al., 1991), biological N fixation, natural abundance (Yoneyama et al., 1990), fertilizer utilization (Angle et al., 1993), mineralization and immobilization (Davidson et al., 1991 , Shen et al., 1984, Stephen et al., 1996), denitrification (Blackmer and Bremner, 1977), plant uptake (Thomsen et al., 1997) and leaching (Hallberg, 1986). The ^{15}N stable isotope is ideal for tracing N through the plant-soil-microbial pathways associated with soil aggregation, soil nitrogen, and plant uptake processes.

Field and lysimeter experiments give more realistic estimations of N transformations and their direct measurement of N recovery than laboratory experiments (Lazzari, 1982). Most studies on ^{15}N labeled residue-decomposition and associated nitrogen transferred to the following crop have used dried leaves, stems, but very few have used roots. Few studies have used *in-situ* labeling of plant material to determine plant uptake of N from foliar fertilizers in the field (Zebarth et al. 1991, Jordan et al., 1996). Zebarth et al.,(1991), reported that foliar-applied urea was absorbed very rapid and 44 to 67% of foliar-applied ^{15}N urea was recovered in tops and roots of soybean (Vasilas et al, 1980).

In this study, we determined whether plant-derived organic N, sequestered at different locations in soil aggregates, affected N absorption by subsequent com crops. Seasonal and spatial distributions of plant-derived organic N were determined in aggregates and sieved to different size classes within concentric regions of aggregates within each size class. Nitrogen released from root and shoot portions of rye cover crops were determined by applying ^{15}N labeled fertilizer to the shoot before cutting or spray killing the rye cover crop.

The objective of this study was to identify the contributions of rye root and shoot N to different regions within aggregates ranging from 2.0 to 9.5 mm across in the A_p horizon of a Kalamazoo loam soil. This objective was evaluated during a two-year field study at the Kellogg Biological Station (KBS), MSU located near Kalamazoo, Michigan.

MATERIALS AND METHODS

Experimental design and treatments

A two- year field experiment (1997-1999) was conducted on 16 Microplots (6 by 10 m) established in August 1994 (Rasse, 1997) on a Kalamazoo loam soil (coarse-loamy, mixed, mesic Typic Hapludalf) at the KBS/LTER (long term ecological research) site in southwestern Michigan. There were four treatments;

1) Bare soil control (C) where all plant life was eliminated by frequent application of Roundup ultra.
2) Bare soil where rye shoots were applied before corn planting (RS).
3) Rye cover crop where shoots were cut and removed and roots in the soil remained *in situ* (RR).
4) Rye cover crop roots and shoots (RRS) where rye shoots were cut and placed on soil surface.

Each treatment was replicated four times in a randomized complete block design. The previous crop from August 94 to April 97 was alfalfa. The alfalfa was spray-killed with a Roundup Ultra application in April 1997 and plots were maintained plant free by adding two applications of Roundup Ultra during the successive seven months. Finely ground limestone was applied to the all plots at the rate of 2 tons/ha on April 4, 1998. No limestone was applied in the Spring of 1999.

^{15}N experiment

Two open-ended PVC cylinders, 30 cm in diameter and 60 cm in depth, were driven through the Ap horizon and into the center of the Bt_2 horizon in each plot by a front fork loader of a tractor. To maintain the balance and prevent damage to the PVC container an iron plate with a cylinder adaptor that fitted outside each PVC chamber facilitated these insertions of the PVC cylinders into soil. The distance between the centers of two cylinders was approximately 75 cm. During the Fall of 1998, 2 additional cylinders were inserted into each plot approximately 75 cm apart from cylinders installed in Spring 1998.

In spring and fall of 1998, approximately 45 rye seeds were planted into each PVC cylinder of the rye treatment plots. In an effort to avoid soil contamination by ^{15}N, the soil surface in each cylinder was covered with plastic sealed around the walls of the PVC cylinder and each row of rye using nontoxic clay sealant. Pine wood shavings were placed on the plastic to absorb any mist or droplets of the ^{15}N labeled spray materials preventing them from contacting the to soil surface. Cylinders with no cover crops also covered plastic cover and pine shavings to receive the same treatments.

Rye plants were labeled with ^{15}N by foliar applications of solutions containing 6.39 g $(^{15}NH_4)_2SO_4$ containing 99 atom% ^{15}N dissolved in 9 L of distilled water in May. This solution was applied in 3 to 4 separate applications to prevent run off. Each time equal amounts of ^{15}N solution (approximately 125 ml) were manually applied rye shoots using graduated spray bottles. All PVC chambers were covered by a plastic webbed-sided clothes-basket securely

anchored to the soil to prevent foliar losses during rain, threatening rain and at night. These covers were removed during sunny days.

Following a two-week translocation period, the rye plants were spray-killed with Roundup Ultra without ammonium sulphate that (4.5 L ha^{-1}) mixed with 186 L ha^{-1} water in early May of 1998 and 1999. Pine wood shavings were cleaned using vacuum cleaner and the plastic cover and clay sealants were removed. Above ground plant parts of rye were manually cut, weighed and subsamples were taken for analyses. Rye shoots were removed or placed on the soil surface inside PVC cylinders with appropriate treatments.

Corn seeds (6-8) were hand planted into each PVC cylinder. Metal screens with 1 cm openings were placed on the top of the soil and secured with nails to prevent residue losses by wind or animal consumption of corn seeds or rye shoots. Each chamber received 500 ml water from the soil surface. Following germination PVC ^{15}N lysimeters were thinned to two corn plants, 2 days after emergence. Thinned corn plants were left on the soil surface of the chambers to retain 100% of ^{15}N within the PVC lysimeters.

Soil sampling

Background soil samples (0-5 and 5-15 cm) were taken from each ^{15}N lysimeters using a small (2.5 cm in diameter) PVC pipe before ^{15}N application. After spray killing of rye, approximately 1 cm soil crust was subsampled from each ^{15}N lysimeters to determine if any ^{15}N soil contamination had occurred

during labeling. There were no significant differences in the soil concentration sampled from labeled and non labeled PVC chambers.

Soil samples for aggregate analyses were extracted from 0-5 and 5-20 cm depths from the soil surfaces by periodically pushing PVC pipe into the soil and removing it using a small garden shovel. Soil samples were air-dried and manually sieved with the 9.5 mm sieve. Aggregates between 2.0-4.0mm, 4.0-6.3mm and 6.3-9.5mm separated into their exterior and transitional layers and interior regions using meso soil aggregate erosion (SAE) chambers. Samples >9.5 mm and < 2 mm were stored in the laboratory for further analyses. In this research only soils from 0-5 cm depth were analyzed. In addition, samples that were sampled in July 1999 sieved into 9 size classes: >9.5, 9.5-6.3, 6.3-4.0, 4.0-2.0, 2.0-1.0, 1.0-0.5, 0.5-0.25, 0.25-0,106, and <0.106 mm and aggregates were analyzed for total N, ^{15}N and SOC.

Rye root and shoot sampling

Rye root and shoot sub samples were taken before and after the ^{15}N labeling to determine initial and final ^{15}N contents of plant shoots and roots.

Rye root samples were extracted from the top 15 cm depth of soil surface by pressing PVC cores (117 cm^3) into the soil to sample rye roots before and after ^{15}N application. Roots were removed from this sample by developing a slurry of distilled water which was poured through a 53 um screen and the retained roots were washed under water. Fine and white roots were picked from

the sand and residue remaining on the screen by tweezers. Both roots and shoots were oven dried at 70°C for 24 h.

Soil and plant analyses

Following the separation of aggregates into 3 equal concentric layers, samples were further processed by grinding in mortar and pestle. Analyses of transitional layers of soil was only performed aggregates sampled in July 1999 (Tables 3.1, 3.2 and 3.3). Transitional layer was in between the exterior layer and the interior region and the concentrations of N and ^{15}N of this layer was similar to one of exterior layers or interior regions depended on aggregate size. Therefore, we limited our aggregate layer analyses only with external layers and internal regions.

Sand was removed by sieving each peeled and ground sample through a 53 um screen to increase the concentration of the ^{15}N and N in the small sample size associated with each concentric layer of each aggregate. Resultant clay and silt samples were weighed into small tin capsules, approximately to 10 mg and 5 decimal accuracy and placed into an autosampler. Total C and N (organic N plus inorganic NH_4 and some NO_3) of plant and soil materials were determined by the dry combustion method (Kirsten, 1983) using a C/N/H analyzer NA 1500 series 2 (Carlo Erba Stumentazione, Milano, Italy) and $\%^{15}N$ by using Isotope Ratio Mass Spectrometer Model 2020 (Europa Scientific, Crewe, UK). Total C content of a Kalamazoo loam soil from 0-5 cm depth was assumed to be equal to soil organic carbon as reported by Santos (1998).

^{15}N signatures in soil aggregate concentric layers were measured and $\delta^{15}N$ and atom $\%^{15}N$ was calculated as below (Yoneyama, 1996):

$$\%^{15}N = [(^{15}N/^{14}N)_{spl} - (^{15}N/^{14}N)_{std} / (^{15}N/^{14}N)_{std}] \times 100 \quad [1]$$

where;

^{15}N = Atom % ^{15}N which gives the absolute number of atoms of a N-15 isotope in 100 atoms of total N element.

$$\text{Atom \% } ^{15}N = [^{15}N / (^{15}N + ^{14}N)] \times 100 \quad [2]$$

^{14}N = Atom % ^{14}N

$$\text{Atom \% } ^{14}N = [^{14}N / (^{15}N + ^{14}N)] \times 100 \quad [3]$$

spl = sample

std=standard (atmospheric N_2)

Aggregate erosion

Concentric layers of aggregates were removed from each aggregate by the meso soil aggregate erosion (SAE) chamber technique reported by Smucker et al. (1999). Briefly, stainless steel chambers having 2.5 cm (ID) diameters and lengths of 3.0 cm, were rotated between 200-250 rpm on a rotary shaker. Peeled soil fell through a 352 μm screen into the base. Aggregates were selected according to their uniform shapes. Priority was given to the most spherical aggregates with no visible roots to minimize errors originating from peeling plant root residues. Three aggregates were selected and peeled from the 6.3-9.5 mm size fraction, 3-4 aggregates from the 4.0-6.3 mm size fraction and 5 aggregates from the 2-4 mm size fraction of each plot in order to obtain adequate sample for

analyses. A single aggregate was weighed, placed in each SAE chamber and covered with aluminum foil. Each SAE chamber was placed in a glass beaker (100 ml) and secured with sponge packing. SAE chambers were placed on rotary platform shaker (Innova, model 2300, New Brunswick Scientific Co. Inc., New Jersey, USA), having a rotational diameter of 2.5 cm. External layers were removed by peeling for about 6 to 90 min at 180-250 rpm. Aggregates that broke were discarded and replaced. This process was repeated, with frequent weighing, until the exterior one third (g/g) was removed. An Excel spreadsheet was used to calculate and predict 33 ±1.5 % (g/g) of each soil aggregate was removed.

Statistical analysis

Treatment effects on measured parameters were estimated by a PROC-GLM procedure using Statistical Analysis System (SAS Institute, 1999). Duncan's multiple range test was used to separate means of measurements. Carbon, nitrogen and ^{15}N contents of exterior and interior layers of soil aggregates were compared by paired t-test using Statistical Analysis System (SAS). Correlation analysis was used to determine relationship between plant and soil parameters. All significant tests were set at the 0.05 level.

RESULTS AND DISCUSSION

Total soil nitrogen (TN)

Soil aggregates, 6.3-9.5 mm across, accumulated the most total N (TN) in their external and transitional layers in the 0-5 cm depth samples in July 1999 (Figure 3.1 and Table 3.1). Total N was not significantly between aggregate layers in June 1998 (Figure 3.2). Greater N concentrations resulted in the highest ratios of external (Ne) to internal (Ni) in July, which diminished through September of 1999 (Figure 3.1). These fluctuations in N concentrations on external regions of larger aggregates reflect greater flux rate of N movement through larger soil pores associated with aggregates 6.3-9.5 mm across. Greater soil Ne in July reflects greater soil and residue N mineralization and agrees with Mendes et al. (1999), who reported that readily mineralizable N content of soil aggregates was greater in June under cereal cover crop treatmenst than those measured in September. They found significantly less amount of mineralizable N under bare fallow treatments than the cover crop treatment.

Exterior layers and transitional (ie., one-third of the soil mass between exterior and interior regions) layers of soil aggregate size fractions 4.0 - 6.3 and 6.3 - 9.5 mm across, retained more soil N than bare (Control) soils when either or both root or/and shoot residues of the rye cover crop were present (Tables 3.1 and 3.2)

Table 3.1. Total nitrogen and carbon concentrations and C:N ratios of whole aggregates, exterior layers, transitional layers and interior regions of aggregates between 6.3 - 9.5 mm at 0-5 cm depths of a Kalamazoo loam soil on July 7, 1999.

	N g kg^{-1}				C g kg^{-1}				C:N			
Treatment	Whole agg.	Exterior	Transition	Interior	Whole agg.	Exterior	Transition	Interior	Whole agg.	Exterior	Transition	Interior
Control	0.80c†	0.99b	0.95c	0.93c	12.20b	12.01ab	11.67c	13.03b	14.58a	12.24a	12.28a	14.13a
Shoot	0.90bc	1.34a	1.71b	1.18bc	10.50b	9.89b	15.69b	13.53b	11.98b	7.69a	9.17ba	11.56a
Root	1.10ab	1.38a	1.55bc	1.08b	13.00ab	12.60ab	15.61b	13.75ab	11.59b	9.53a	10.07a	12.87a
Root+shoot	1.30a	1.60a	1.87a	1.39a	18.80a	18.03a	18.18a	16.40a	11.90b	11.30a	9.72a	11.77a

† Values followed by the same letter within same column and between treatments are not significantly different at $p>0.05$ according to Duncan's test.

Table 3.2 Total nitrogen and carbon concentrations and C:N ratios of whole aggregates, exterior layers, transitional layers and interior regions of aggregates between 4.0 – 6.3 mm at 0-5 cm depths of a Kalamazoo loam soil on July 7, 1999.

	N g kg^{-1}				C g kg^{-1}				C:N			
Treatment	Whole agg.	Exterior	Transition	Interior	Whole agg.	Exterior	Transition	Interior	Whole agg.	Exterior	Transition	Interior
Control	0.90bt	1.30b	1.42b	1.30b	11.20b	10.49b	13.3b	13.54a	12.21a	8.08a	9.30a	11.20b
Shoot	1.20b	1.58ab	1.58ab	1.67ab	14.30b	13.65ab	15.7ab	13.59a	11.56a	8.75a	9.93a	8.23ab
Root	1.20b	1.60ab	1.74a	1.90a	13.70b	14.38ab	15.02ab	14.17a	11.85a	9.08a	8.63a	7.47ab
Root+shoot	1.60a	1.80a	1.72a	1.80ab	19.70a	17.49a	16.88a	17.00a	12.10a	9.65a	9.81a	9.45a

† Values followed by the same letter within same column and between treatments are not significantly different at $p>0.05$ according to Duncan's test.

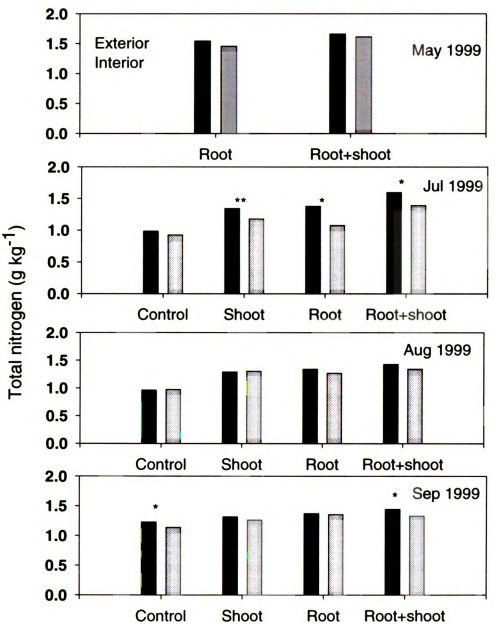

Figure 3.1. Total nitrogen (TN) concentrations of exterior layers and interior regions of 6.3- to 9.5 mm soil aggregates from 0-5 cm depth of a Kalamazoo loam soil in 1999. Significant differences between exterior layers and interior regions of aggregates within the same treatment at the p< 0.05 (*) and p< 0.005 (**) probability levels.

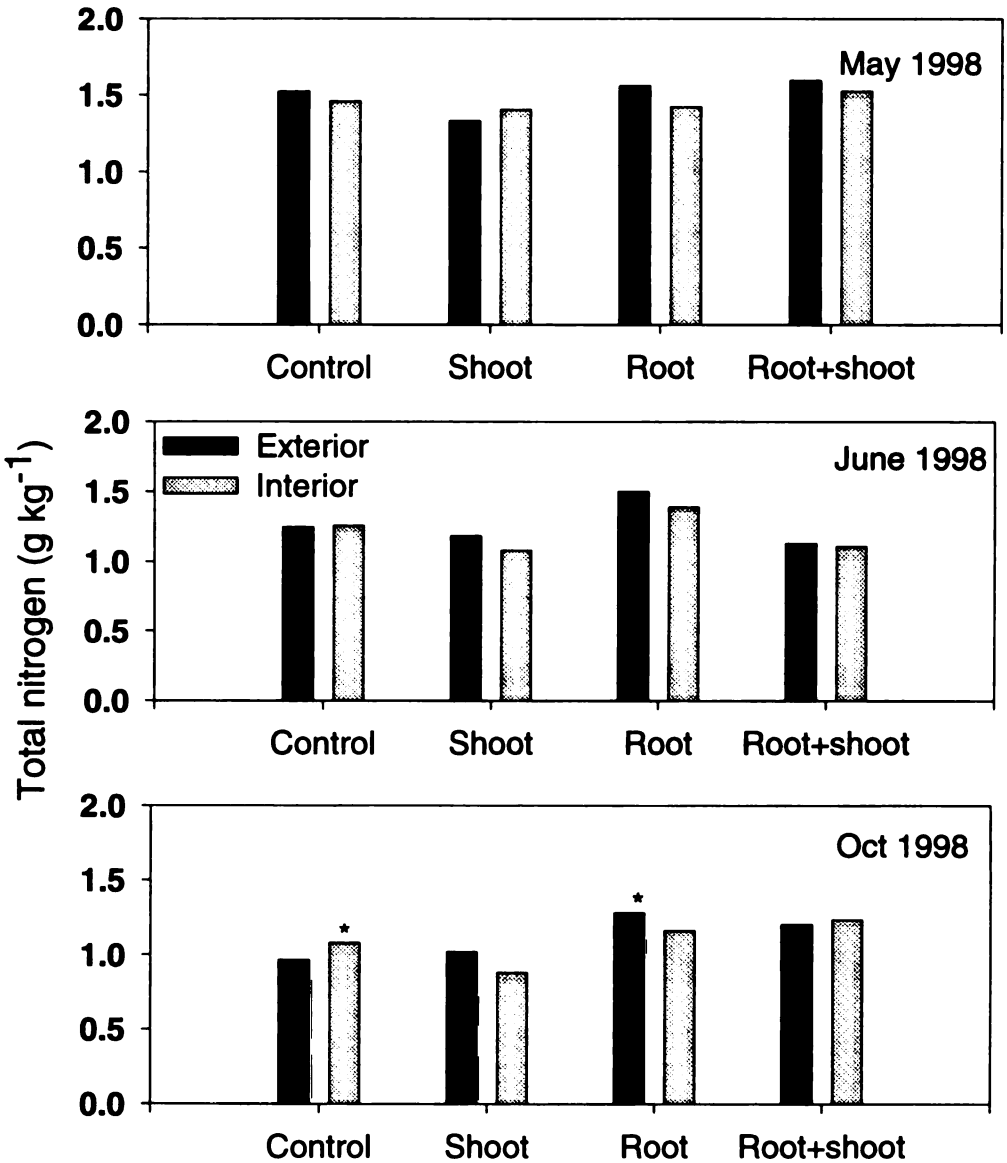

Figure 3.2. Total nitrogen (TN) concentrations of exterior layers and interior regions of 6.3- to 9.5 mm soil aggregates from 0-5 cm depth of a Kalamazoo loam soil in 1998. Significant differences between exterior layers and interior regions of aggregates within the same treatment at the $p < 0.05$ (*) and $p < 0.005$ (**) probability levels.

Total nitrogen concentrations were greater in microaggregates in most treatments except root+shoot treatment, where there were no significant differences in TN observed among different aggregate sizes (Figure 3.3). Transition layers of smaller aggregates, 2.0 – 4.0 mm across, retained significantly higher TN compared to other layers of aggregates (Table 3.3) suggesting more transient flow of N across the entire regions of these smaller soil aggregates. Smaller aggregates also have better oxygen supply in their internal regions (Sextone et al., 1985). Consequently, the turnover rates of N and possibly SOM appear to be greater in the interior regions of smaller than larger aggregates. If there is a homogenous distribution of SOM during the hierarchial processes of soil aggregate formation (Oades and Waters, 1991), then N concentrations should be similar in all exterior layers and interior regions of all sizes of soil aggregates. These reported N gradients suggest alternative formation processes involving concentric deposits of organo-mineral fractions to exteriors of expanding size fractions of soil aggregates.

Whole soil aggregates generally had N concentrations that were lower or equal to N in exterior and transitional layers and interior regions of the same size soil aggregates (Tables 3.1, 3.2 and 3.3). Similar results were observed for some of the treatments by Santos (1998). Total N contents within whole soil aggregates are expected to be in the same range as maximum and minimum N concentrations obtained for exterior layers and interior regions of soil aggregates. One reason for the different (lower) N concentrations for whole aggregates may be the relative heterogeneity of different soil aggregates as analyses of whole

and peeled aggregates were on different aggregates randomly selected from the same whole soil sample.

Sixty soil aggregates having a size fraction between 4.0 - 6.3 mm across and sampled from a 0-5 cm soil depth in the same ^{15}N lysimeter of the rye root (RR) treatment, were analyzed for TN, SOC and ^{15}N. The average TN value for 60 aggregates was 1.3 g kg^{-1} having a C.V of 15%. The average SOC value was 12.2 g kg^{-1} with a C.V of 19% for the same 60 aggregates. Therefore, there appears to be considerable variation, of at least these two parameters, among individual soil aggregates from the same volume of soil. Therefore, soil heterogeneity is our best explanation for this discrepancy. Further studies are needed, however, to verify this conclusion.

Table 3.3. Total nitrogen and carbon concentrations and C:N ratios of whole aggregates, exterior layers, transitional layers and interior regions of aggregates between 2.0 – 4.0 mm at 0-5 cm depths of a Kalamazoo loam soil on July 7, 1999.

	N g kg^{-1}				C g kg^{-1}				C:N			
Treatment	Whole agg.	Exterior	Transition	Interior	Whole agg.	Exterior	Transition	Interior	Whole agg.	Exterior	Transition	Interior
Control	1.00c†	1.09a	1.43a	1.10a	11.40b	14.73a	13.99a	15.13a	11.67a	14.48a	9.78a	14.13a
Shoot	1.20b	1.04a	1.59a	0.88a	12.60ab	13.67a	13.59a	13.18a	11.00a	15.21a	8.55a	11.56a
Root	0.90c	1.01a	1.36a	1.06a	9.90b	13.12a	14.75a	15.26a	11.56a	14.56a	10.845a	12.87a
Root+shoot	1.50a	0.91a	1.56a	0.99a	17.20a	13.63a	16.47b	13.96a	11.60a	14.46a	10.56a	11.77a

† Values followed by the same letter within same column and between treatments are not significantly different at $p>0.05$ according to Duncan's test.

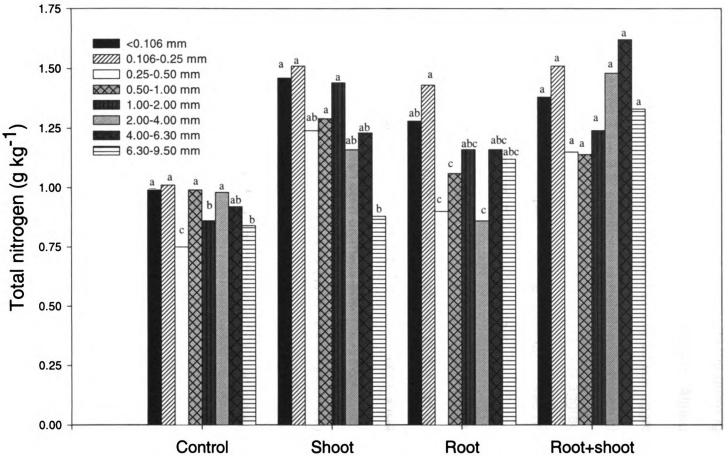

Figure 3.3. Total soil nitrogen (TN) concentrations in aggregate size fractions from 0-5 cm depth of a Kalamazoo loam soil in July 1999. Values followed by the same letter within a treatment and between aggregate size fractions are not significantly different at p>0.05 according to Duncan's multiple range test.

Gradients in N concentrations within soil aggregates, as indicated by the ratio of Ne to Ni (Ne/Ni), for soil aggregates 6.3-9.5 mm across became smaller and the difference of the ratios became greater as the growing season of corn progressed (ie., aboveground corn biomass increased). Although nitrogen concentrations in exterior layers increased in July as soil aggregate size increased, Tables 3.1 – 3.3, significant correlations between changes in ratios of Ne/Ni and corn biomass were observed for only largest aggregates measured (6.3-9.5 mm) which were sampled from rye cover crop plots (r^2=0.71) and no rye cover cropped plots (r^2=0.88), Figures 3.4 and 3.5.

No significant correlations were observed between changes in Ne/Ni ratios and the biomass of corn, during early growth nor at the end of the corn growing season, for soil aggregates 2.0-4.0 and 4.0-6.3 mm across (data not shown). The lack of correlation between corn biomass and TN in aggregates sizes smaller than 6.3 mm may be due to the shorter distances between exterior layers and interior regions within smaller aggregates. Mineralized N, as soil NO_3 form, can rapidly diffuse into and out of centers of smaller soil aggregates quickly and become less available for plant uptake. Rye treatments appeared to have no influence on TN concentrations in of exterior layers nor and interior regions of 2-4 mm aggregates in July, 1999 (Table 3.3). When whole aggregates were crushed and analyzed for TN, rye root+shoot treatments contributed the most N to these small aggregates ($p<0.05$).

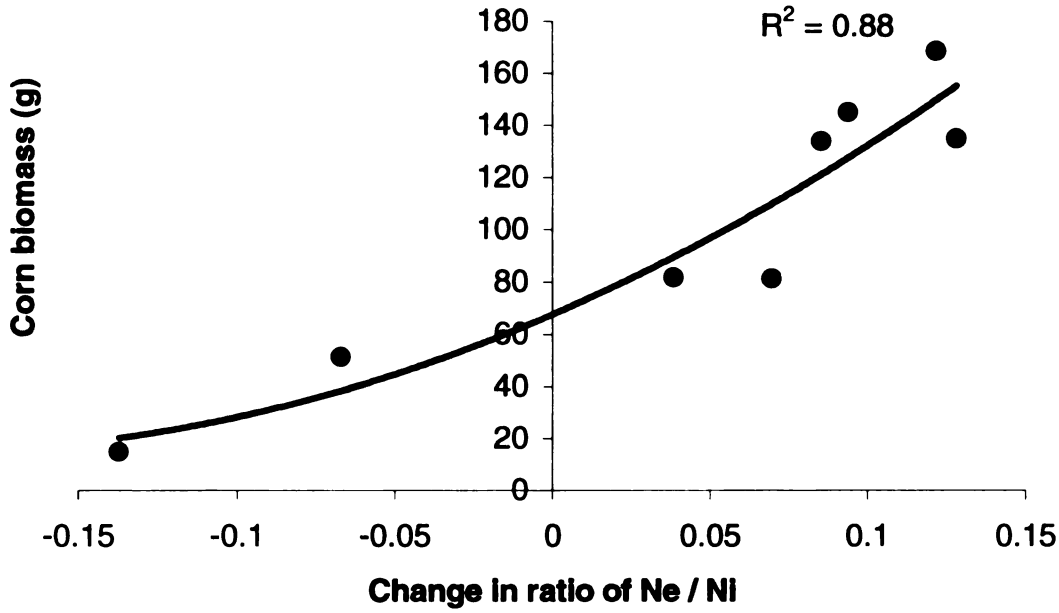

Figure 3.4. Relationship between change in the ratio of N concentration of exterior layer to interior region (Ne /Ni) of 6.3 - 9.5 mm soil aggregates from July 1999 to September 1999 and corn biomass at harvest of no-rye cover crop.

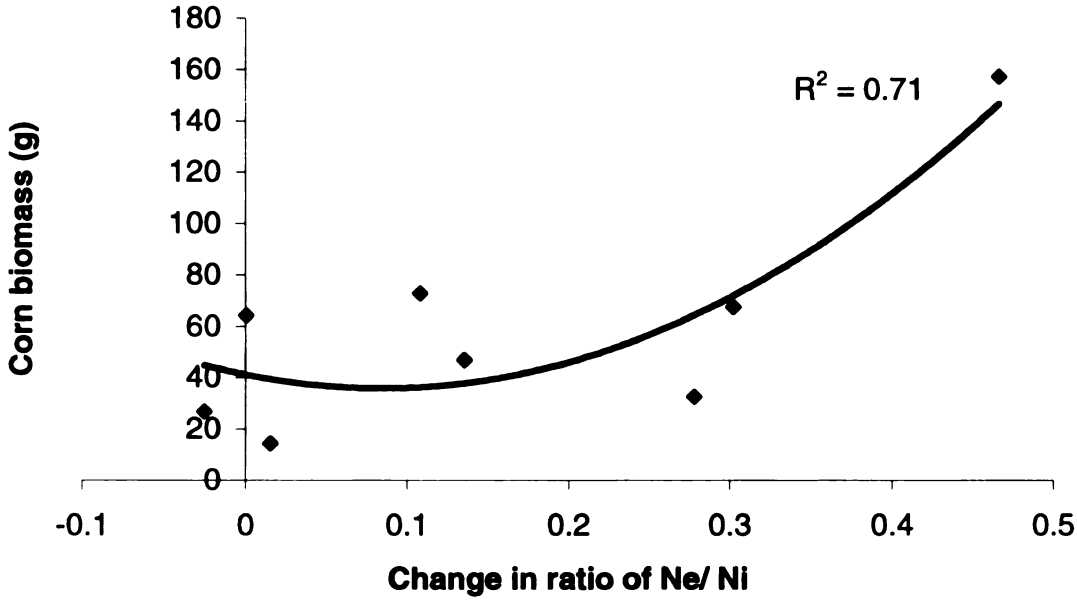

Figure 3.5. Relationship between change in the ratio of N concentration of exterior layer to interior region (Ne /Ni) of the 6.3 - 9.5 mm soil aggregates from July 1999 to September 1999 and corn biomass at harvest of rye cover crop treatments.

Rye shoot mulching appeared to contribute more than *in situ* rye roots, to whole aggregate N concentrations (Table 3.3, Figure 3.6). Therefore, it is concluded that deposition of N, originating from decomposing rye roots and shoots, onto soil aggregates caused larger gradients to develop within the concentric layers of larger aggregates during the growth of a subsequent corn crop. Rye root + shoot treatments contributed the most TN and ^{15}N to soil aggregates than the separate contributions of either *in situ* rye roots or shoot mulches.

Nitrogen gradients between the external layers and internal regions of soil aggregates 6.3-9.5 mm across were greatest in July, when compared to August or September of 1999 (Figure 3.1). Nitrogen isotope transfer from rye to concentric layers within soil aggregates (Figures 3.6 and 3.7) suggest rapid transfer of ^{15}N from dying roots and shoots to soil aggregate surfaces soon after the spray-killing of rye. Decomposing roots and shoots contribute large quantities of C and N to soils (Huntjens, 1971, Cheng and Coleman, 1990, Mary et al., 1993, Ehrenfeld et al., 1997). Although, mineralization of N compounds can be inhibited by living and dying plant components, much of the mineralized N, derived from dead roots or root exudates is immobilized by the microorganisms due to addition of C to the medium. Microorganism utilization of N from the rye cover crop is a highly probable explanation since C:N ratios of rye roots were greater than fifty at the sampling date. If C:N ratio of plant residue is greater than 25:1, N will be taken from the inorganic N pool and decomposition continue

slowly until the death of microbial population (Paul and Clark, 1996). Therefore measured total N included recently decomposed residue N, soil N and microbial biomass N in July 1999. N mineralization from rye root and shoot residue increased in July and resulted in N gradients of 6.3-9.5 mm aggregates (Figure 3.1) as it was also reported by Mendes et al., (1999). Roots can influence chemical composition of soil they contact by absorbing water and nutrients and by releasing C rich root exudates. Root uptake of water creates greater and more frequent wetting and drying cycles, which increases SOM degradation. This mineralized N is utilized by corn and/or lost from the soil during corn growth. Total N concentrations decreased from spring to harvest (Figures 3.1 and 3.2).

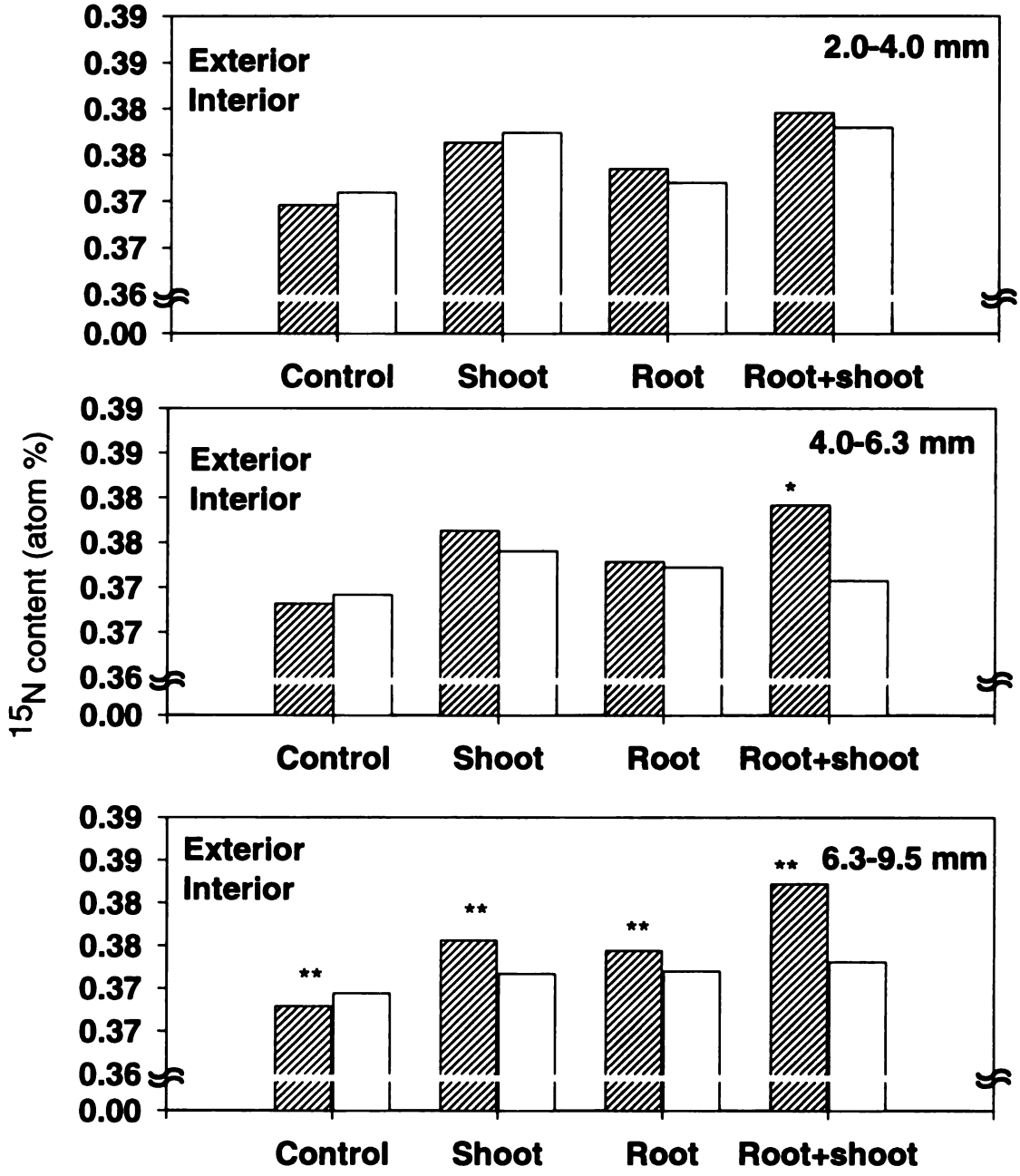

Figure 3.6. Total ^{15}N contents of exterior layers and interior regions of 2.0-4.0, 4.0-6.3 and 6.3-9.5 mm aggregates from control, shoot, root and root+shoot treatments of the Kalamazoo loam soil on July 1999 . Significant differences between exterior layers and interior regions of aggregates within the same treatment at the $p< 0.05$ (*) and $p< 0.005$ (**) probability levels.

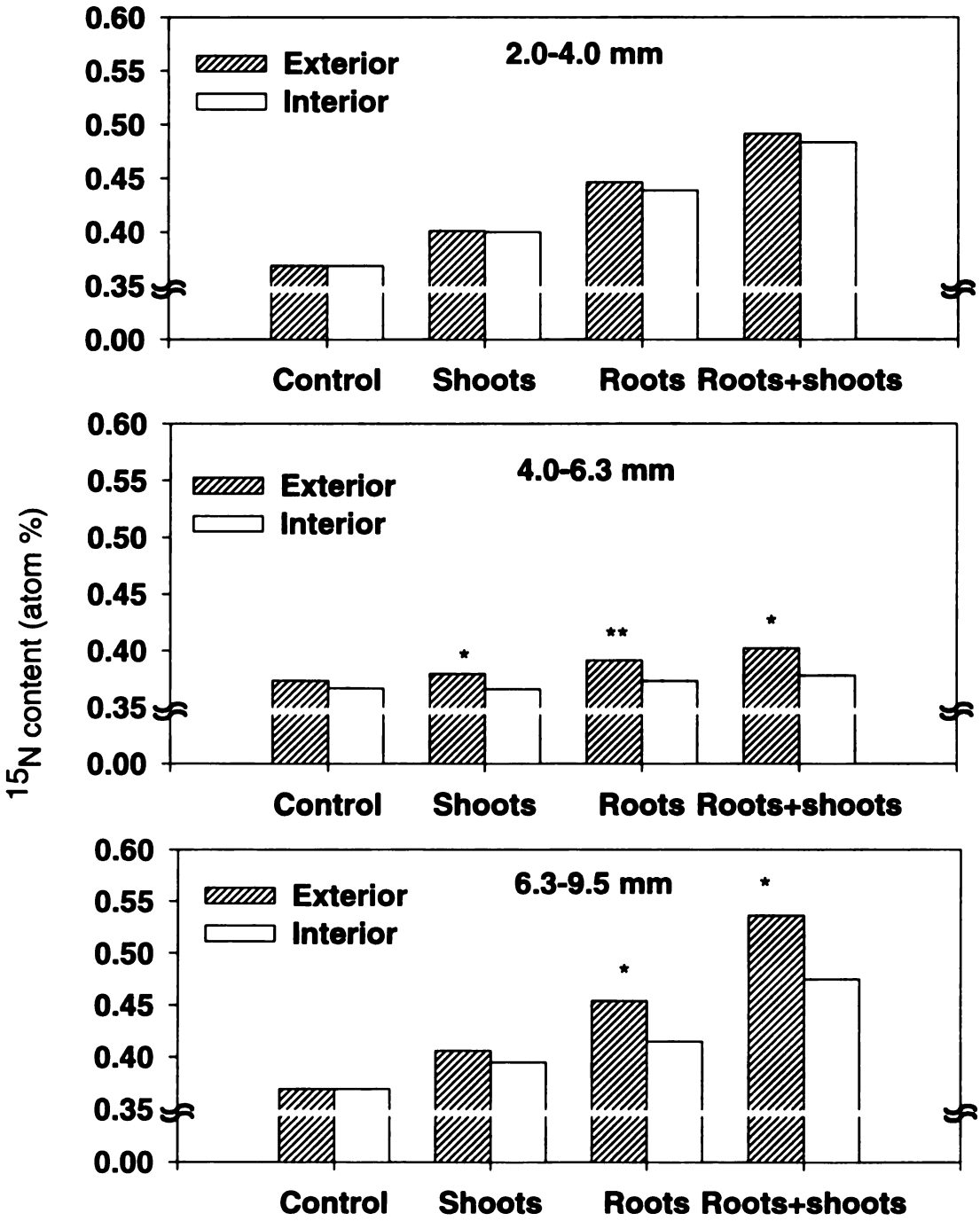

Figure 3.7. Total ^{15}N contents of exterior layers and interior regions of 2.0-4.0, 4.0-6.3 and 6.3-9.5 mm aggregates from control, shoot, root and root+shoot treatments of the Kalamazoo loam soil on June, 1998 . Significant differences between exterior layers and interior regions of aggregates within the same treatment at the $p< 0.05$ (*) and $p< 0.005$ (**) probability levels.

Rye root and shoot derived nitrogen

Distribution of ^{15}N among the full range of aggregate size fractions extracted from bulk soils of the three rye cover crop treatments showed trends of greater ^{15}N contents in smaller aggregates and lesser ^{15}N contents in larger aggregates (Figure 3.10). Microaggregates (<0.25 mm) retained the second highest rye-derived ^{15}N. This suggests more uniform distributions of ^{15}N within the smaller aggregates and possible ^{15}N gradients established within larger aggregates. Nitrogen from rye roots and shoots could be detected on the exterior layers of soil aggregates of 4.0 - 6.3 and 6.3 - 9.5 mm as early as 17 days after rye shoot applications to the soil surface in 1998 (Figure 3.7). Rye root contributions of N were greater than that of rye shoot N, presumably due to the more rapid decomposition and direct contact of rye roots to soil aggregates. Contrasting gradients of ^{15}N, derived from rye increased with increasing aggregate size (Figure 3.7). Similar increases of ^{15}N gradients with aggregate sizes were also observed in July 1999, during the second year of these experiments (Figure 3.6). These results support that most of roots grow preferentially around surfaces of soil aggregates rather than through aggregates. Although concentrations of ^{15}N on surface layers and interior regions of aggregates 2.0-4.0 mm across were the same as the surface layers of larger aggregates, no gradients of ^{15}N from rye cover crops were observed for aggregates 2.0-4.0 mm across (Figures 3.6 – 3.9). Organic materials derived from rye roots and shoots appeared to be uniformly distributed throughout aggregates 2.0 - 4.0 mm across with minimum ^{15}N gradients at the beginning of

the corn growing season (Figures 3.6 and 3.7). Contents of ^{15}N within aggregates 2.0 - 4.0 mm across decreased with no gradients were observed at harvest (Figure 3.8). The ^{15}N gradients developed within larger soil aggregates, 6.3-9.5 mm across, decreased in October 1998, 116 days after rye shoot application (Figure 3.8). Nitrogen isotope gradients between external layers and internal regions of soil aggregates 4.0 – 6.3mm across developed early in the summer (Figure 3.7) diminished as the season progressed (Figure 3.8). Exterior layer of soil aggregates contained similar concentrations of ^{15}N as interior regions at corn harvest (Figures 3.8 and 3.9). In summary, there seemed to be a migration of ^{15}N materials from rye roots and shoots into soil aggregates at a constant rate. Early in the season, more ^{15}N migrated to the interior regions of the smallest aggregates, 2 – 4mm across, but was limited to only surfaces and transitional regions of the larger aggregates, 6.3 – 9.3 mm across. At harvest, more of the ^{15}N located within interior regions of the smallest sized aggregates was withdrawn by corn growth while more ^{15}N remained within the interior regions of the medium sized aggregates, 4 – 6.3 mm across (Figures 3.7-3.8 and 3.6 - 3.9.

Mineralization of SOM may be more rapid on the surfaces of soil aggregates and may be stimulated by growing corn roots (Sanchez, et al., 2000). Living roots provide large quantities of C compounds to the surfaces of soil aggregates (Santos, 1998) promoting microbial biomass activities and greater N mineralization (Texier and Billes, 1990). Therefore, corn roots appear to be important C sources for stimulating microorganisms in the soil. Their specific locations on soil aggregates of different sized fractions need further investigation.

When roots preferentially grow on the surfaces of soil aggregates, as discussed above, these roots should increase N mineralization in the external regions of aggregates. Frequent wetting-drying cycles will diffuse more N into interior regions of soil aggregates of all sizes. Mean-free pathways, however, limit the diffusive distance or depths within aggregates of different size fractions. However, when roots are present or when soil water contents are high, highly mobile mineral N, located on surface layers of larger aggregates and throughout smaller aggregates can either be absorbed or leached from these respective areas of multiple sized soil aggregates with subsequent diffusion from their interior regions towards their exterior regions. The good correlation (r^2=0.68) between ^{15}N ratio of exterior layers to interior regions of soil aggregates and ^{15}N uptake by corn plant support these conclusions. Similar correlations were found between changes in the ratios of total N of external layers and internal regions of soil aggregates at the beginning and end of the corn growing season and corn biomass (Figures 3.4 and 3.5) in 1999. Increases in the ratios of Ne/Ni (in July) – Ne/Ni (in September) demonstrate root uptake of N during the corn growing season. As these ratios increased, greater corn biomass was observed (Figures 3.4 and 3.5). Thus, it is clear that uptake of N is more efficient from the surface of aggregates from a Kalamazoo loam soils larger than 4 mm across.

Most of the ^{15}N presented in the interior regions of soil aggregates greater than 4 mm across was preserved at the time of corn harvest. Especially since many of the roots appear to grow around exterior regions of soil aggregates (Allison, 1973, Whiteley and Dexter, 1983). It was also observed that

approximately 20% of the aggregates contained some of the finer roots which had penetrated and passed through soil aggregates. These soil aggregates containing roots were not selected for analyses. Any fine rye root fragment located within aggregates of any size would result in the deposition of mineralized ^{15}N which could be sequestered within larger aggregates and become unavailable to corn roots unless they penetrated the same larger soil aggregate (Rasse and Smucker, 1999).

More rye root-derived N accumulated on exterior layers of soil aggregates 6.3 - 9.5 mm across than rye shoot-derived N (Figure 3.7). In the first year of experiment soil aggregate samples were taken 17 days after application of labeled rye shoots on the PVC chambers. During the labeling period some ^{15}N was transferred from rye shoots to roots and was released to soil by rye roots as root exudates. During applications of Round Up and cutting rye shoots, dead roots continued to release N compounds to the soil. Therefore, more rye root-derived N was deposited on the exterior layers of aggregates in 1998 (Figure 3.7). In the second year of the experiment, first samples were taken 51 days after application of labeled rye shoots. During that time root derived N was already utilized by corn and shoot derived N concentration was greater than root derived N (Figure 3.6).

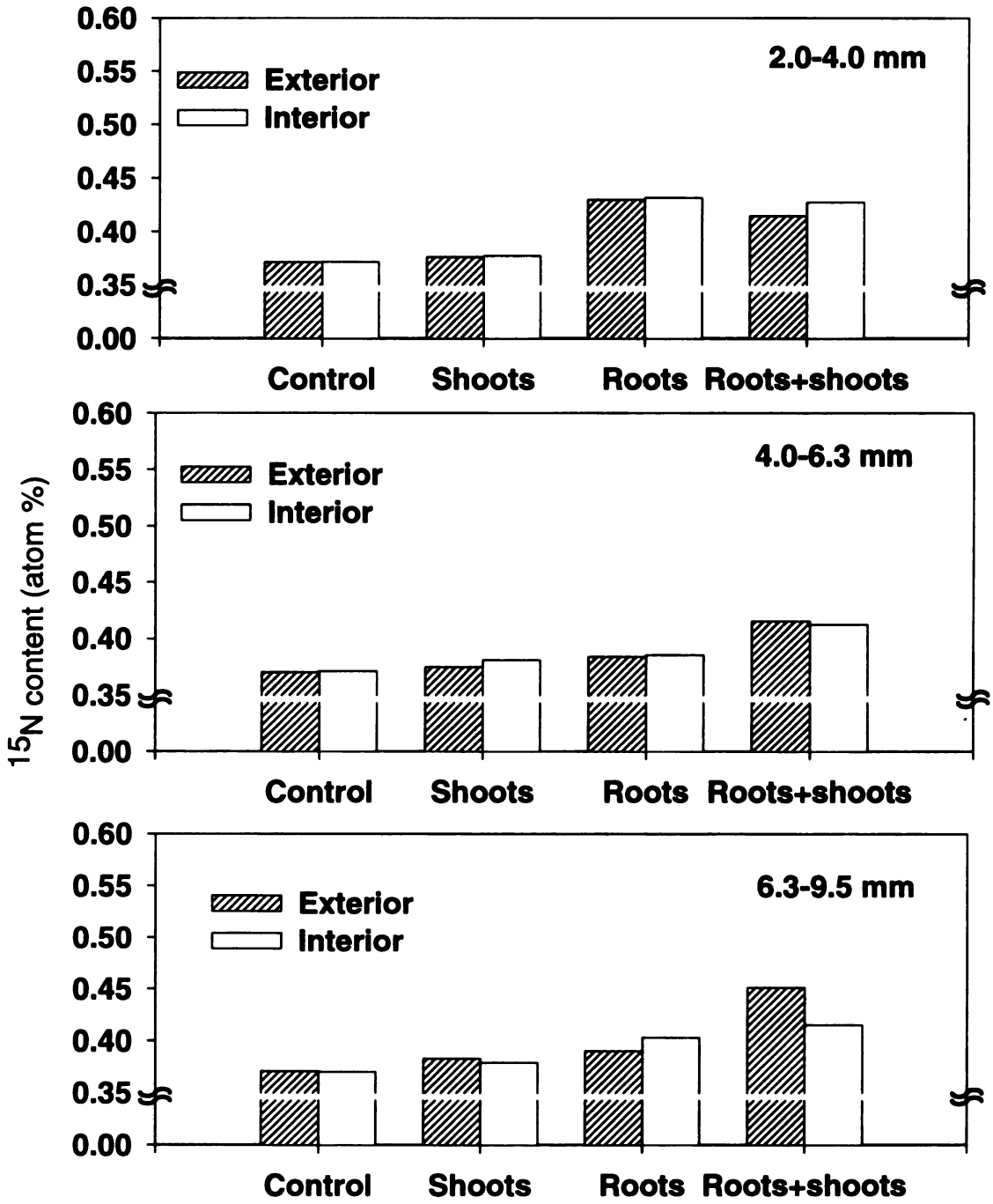

Figure 3.8 . Total ^{15}N contents of exterior layers and interior regions of 2.0-4.0, 4.0-6.3 and 6.3-9.5 mm aggregates from control, shoot, root and root+shoot treatments of the Kalamazoo loam soil on October 1998 . Significant differences between exterior layers and interior regions of aggregates within the same treatment at the $p< 0.05$ (*) and $p< 0.005$ (**) probability levels.

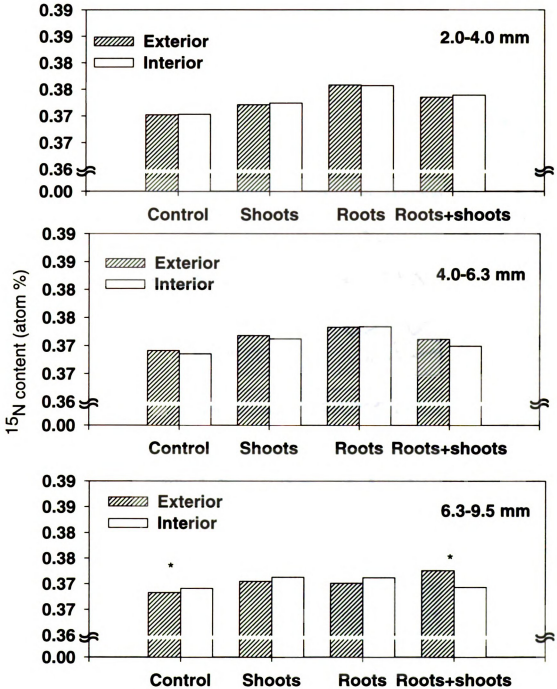

Figure 3.9. Total ^{15}N contents of exterior layers and interior regions of 2.0-4.0, 4.0-6.3 and 6.3-9.5 mm aggregates from control, shoot, root and root+shoot treatments of the Kalamazoo loam soil on September, 1999 . Significant differences between exterior layers and interior regions of aggregates within the same treatment at the p< 0.05 (*) and p< 0.005 (**) probability levels.

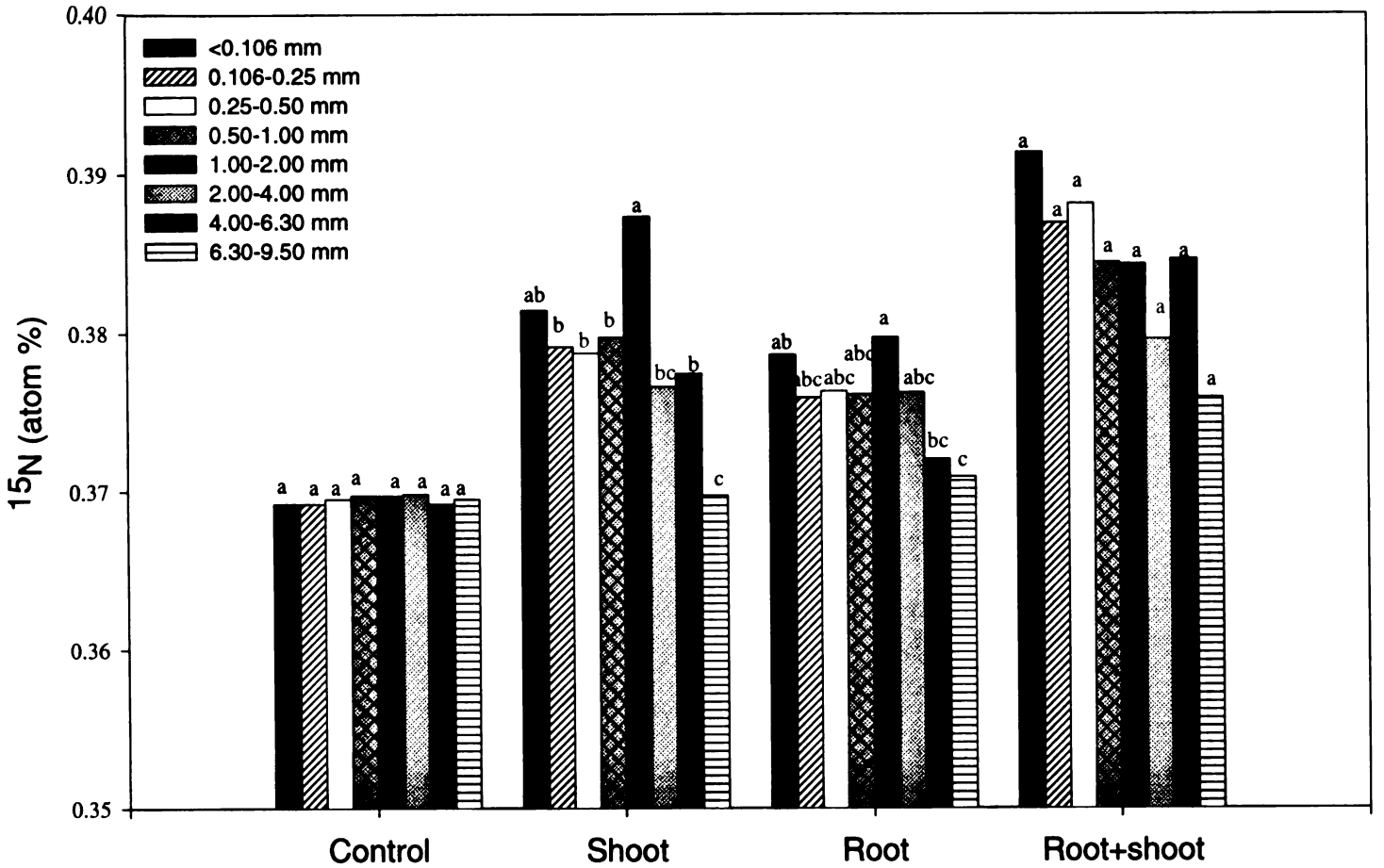

Figure 3.10. Concentrations of ^{15}N in aggregate size fractions sampled from 0-5 cm depths of a Kalamazoo loam soil in July 1999. Values followed by the same letter within each treatment and among aggregate size fractions are not significantly different at p>0.05 according to Duncan's multiple range test, n=4.

Nitrogen derived from rye shoots, roots and root plus shoots were not significantly different for aggregates 2.0 - 4.0 and 6.3 - 9.5 mm across when whole soil aggregates were analyzed (Table 3.4). However, separation of external layers of individual aggregates demonstrated the contributions of short-term rye shoot, root and shoot plus root to soil N pools.

Nitrogen derived from root (N_{dfr}) and shoot (N_{dfs}) located in the exterior layers diminished from planting to harvest (Figure 3.11). The percentage of total N derived from rye shoot and rhizodeposition from rye roots was calculated using equation [1], described in Chapter 4 (Kavdir,. 2000) Exterior layers of aggregates 6.0 - 9.5 mm across retained 1.6% of the N_{dfr} in July 1999, three times more than their interior regions (Figure 3.11). This was slightly greater than the $\%N_{dfs}$. One month later, during the corn growing season $\%N_{dfr}$ and $\%N_{dfs}$ were nearly equal in exterior layers and interior regions of soil aggregates, possibly due to diffusion within larger aggregates and uptake by corn. At harvest, there were greater or equal quantities of rye-N located in interior regions compared to exterior layers of aggregates.

In the case of N fertilization, diffusion rate of N from exterior layers to interior regions of aggregates and even leaching could be faster limiting availability of N to the plant. Kinyangi (2000), reported that if there is more P in the exterior layers of soil aggregates, 4.0-8.0 mm across, than interior regions at the beginning of corn season, corn roots can easily utilize this P resulting in increased corn yield. Aggregate sizes used in this study covered only 34% of the total soil by weight. Additional research on the best management practices for

maintaining more N on surfaces of larger soil aggregates during crop growth as well as sequestering mobile soil N within larger soil aggregates during wet soil periods between cash crops needs to be completed

Aggregates greater than 2 mm contain many longer roots and hyphae than microaggregates (Jastrow and Miller, 1998 and Degens et al., 1994). Aggregates greater than 2 mm had 150 times longer hyphal lengths per aggregate than aggregates smaller than 0.5 mm. Aggregates greater than 2 mm also had 7 times longer root lengths within compared to soil aggregates 1.0-2.0 mm across (Degens et al., 1994). Therefore, main stabilizing factors for macroaggregates are roots, root derived materials and hyphae. While rye and corn roots develop between the planes of weakness and along surfaces of aggregates, root derived materials also help to stabilize macroaggregate surfaces. Continuous addition of SOM through dead and leaving roots and uptake of nutrients and waters by roots contributes development and stabilization of soil aggregates.

If we assume the aggregate hierarchy model, proposed by Oades and Waters (1991) is the only model for the soil structure formation of the Kalamazoo loam soil, then macroaggregates should consist of mostly microaggregates and properties of the macroaggregates should be similar all the way across the aggregate. The formation and function of soil macroaggregates are very dynamic processes utilizing many biogeochemical factors. These factors include: continuous additions of C and N compounds by roots (Santos et al., 1998, Kavdir, 2000); additions of N and P by fertilizers (Kinyangi, 2000); weathering of

clay minerals by water, microbes and roots (Santos et al., 1997); dessication of aggregates by the uptake of water by plant roots (Sissoko, 1997); nutrient extraction by plant roots and leaching; frequent wetting and drying cycles and countless microbial activities (Guggenberger et al., 1999) all appear to develop concentric layers of various properties into the interior regions of soil aggregates. In a summary, it was found that concentric gradients of rye residue-derived N increased with aggregate size. The location of the N within soil aggregate played an important role on corn N uptake. Rye root and shoot derived N in exterior layers of larger aggregates decreased by time. Therefore these studies suggest increasing soil aggregate size and maintaining active plant root systems are the best strategies for maximizing soil N availability to cash cropping systems and reducing N leaching.

Table 3.4. ^{15}N concentrations of whole aggregates, exterior layers and interior regions of aggregates between 2.0–4.0 mm, 4.0 – 6.3 mm and 6.3 – 9.5 mm at 0-5 cm depths of Kalamazoo loam soil on July 7, 1999.

	Atom %^{15}N								
	2.0-4.0 mm			4.0-6.3mm			6.3-9.5 mm		
Treatment	Whole agg.	Exterior	Interior	Whole agg.	Exterior	Interior	Whole agg.	Exterior	Interior
Control	0.370b†	0.370b	0.369b	0.370c	0.368d	0.369a	0.370a	0.368c	0.369b
Shoot	0.377a	0.376ab	0.377a	0.377b	0.376b	0.374a	0.370a	0.375b	0.372ab
Root	0.376a	0.373ab	0.372ab	0.374b	0.370c	0.372a	0.371a	0.374b	0.372ab
Root+shoot	0.380a	0.380a	0.378a	0.378a	0.379a	0.373a	0.376a	0.382a	0.373a

† Values followed by the same letter within same column and between treatments are not significantly different at $p>0.05$ according to Duncan's test.

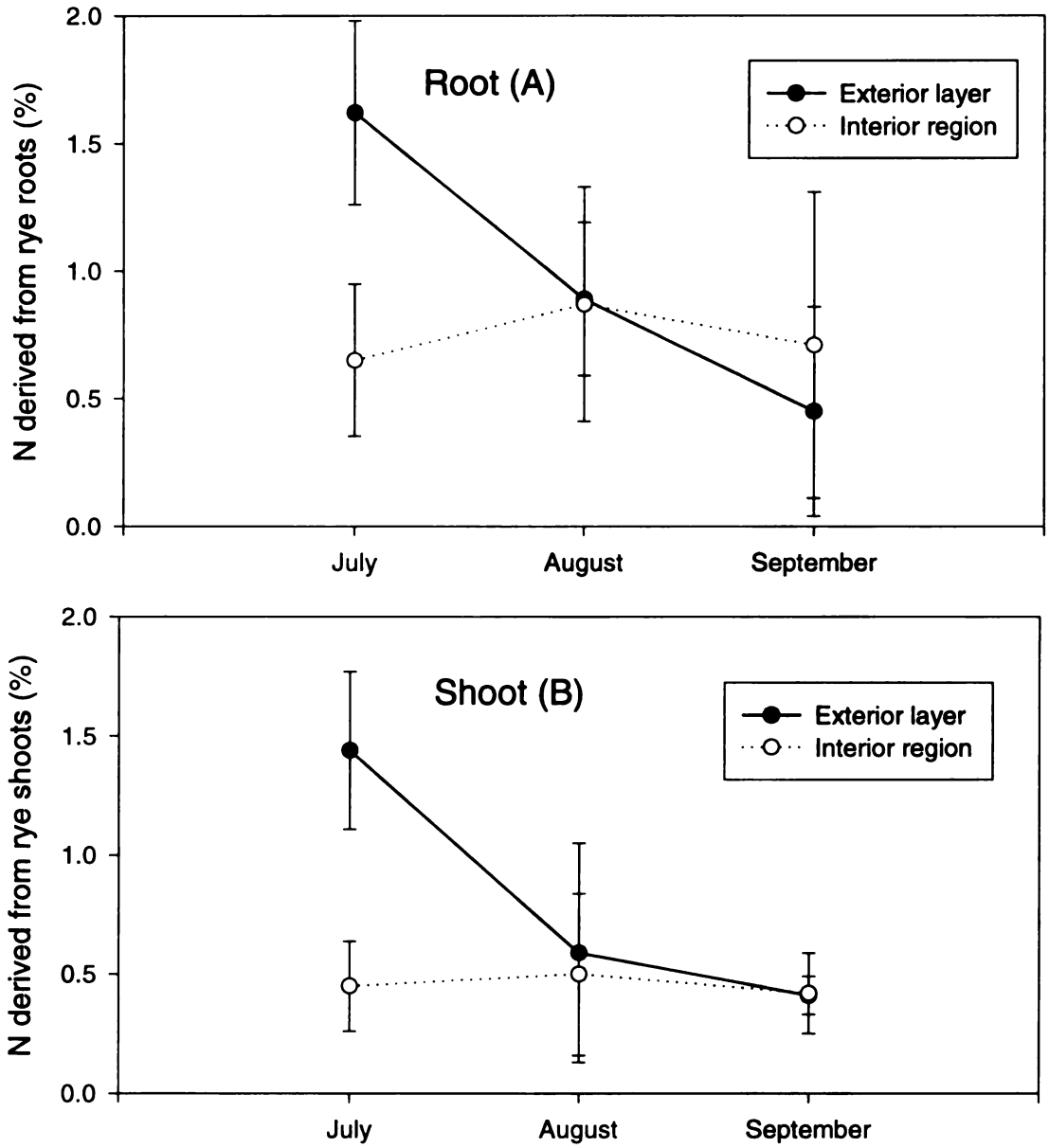

Figure 3.11. Percentage of N derived (A) from rye roots (%Ndfr) and (B) shoots (%Ndfs) in the exterior layers and interior regions of 6.3-9.5 mm soil aggregates from 0-5 cm depth of a Kalamazoo loam soil in July, August and September 1999. Bars represent standard deviations for n=4.

Aggregate erosion rate

Soil eroded from aggregate layers was reduced from 2-10 fold by rye cover crop. Exterior soil layers peeled from 2.0-4.0 mm aggregates were 4.8 times more resistant in rye treatments than those from no rye treatments. (Figure 3.12). Transitional layers peeled from 2.0-4.0 mm soil aggregates from rye treatments were 10.6 times more resistant for rye treatments than those from no rye cover treatments.

Exterior soil layers peeled from 4.0-6.3 mm aggregates were 1.7 times more resistant in rye treatments than those from no rye treatments. (Figure 3.12). Transitional layers peeled from 4.0-6.3 mm soil aggregates from rye treatments were 2.0 times more resistant for rye treatments than those from no rye cover treatments.

Exterior soil layers peeled from 6.3-9.5 mm aggregates were 2.1 times more resistant in rye treatments than those from no rye treatments. (Figure 3.12). Transitional layers peeled from 6.3-9.5 mm soil aggregates from rye treatments were 1.4 times more resistant for rye treatments than those from no rye cover treatments.

Smaller (2.0-4.0) mm aggregates were much more resistant to erosion than larger aggregates and rye contribution to aggregate stability of 2.0-4.0 mm aggregates were much more distinctive than those of aggregates greater than 4 mm. Eroded soil weight per minute increased with increasing aggregate sizes. Erosion rates (mg min^{-1}) of soil materials from external layers were significantly

greater than those extracted from transitional layers for all three soil aggregate fractions from control (no rye) treatments (Figure 3.12).

Dapaah and Vyn, (1998), reported that aggregate stability was higher following cover crops (ryegrass, red clover and oilseed radish) than where no cover crops were used. Raimbault and Vyn, (1991) also reported that under cover crop treatments wet soil aggregate stability was greater than those of no cover treatments. Results from Meso SAE chambers also confirmed that aggregates from rye cover crop treatments were much more resistant to erode than those from no rye cover crop treatments. Meso SAE chambers can be used to compare short term cropping systems affects on soil aggregate stability for different locations of aggregates.

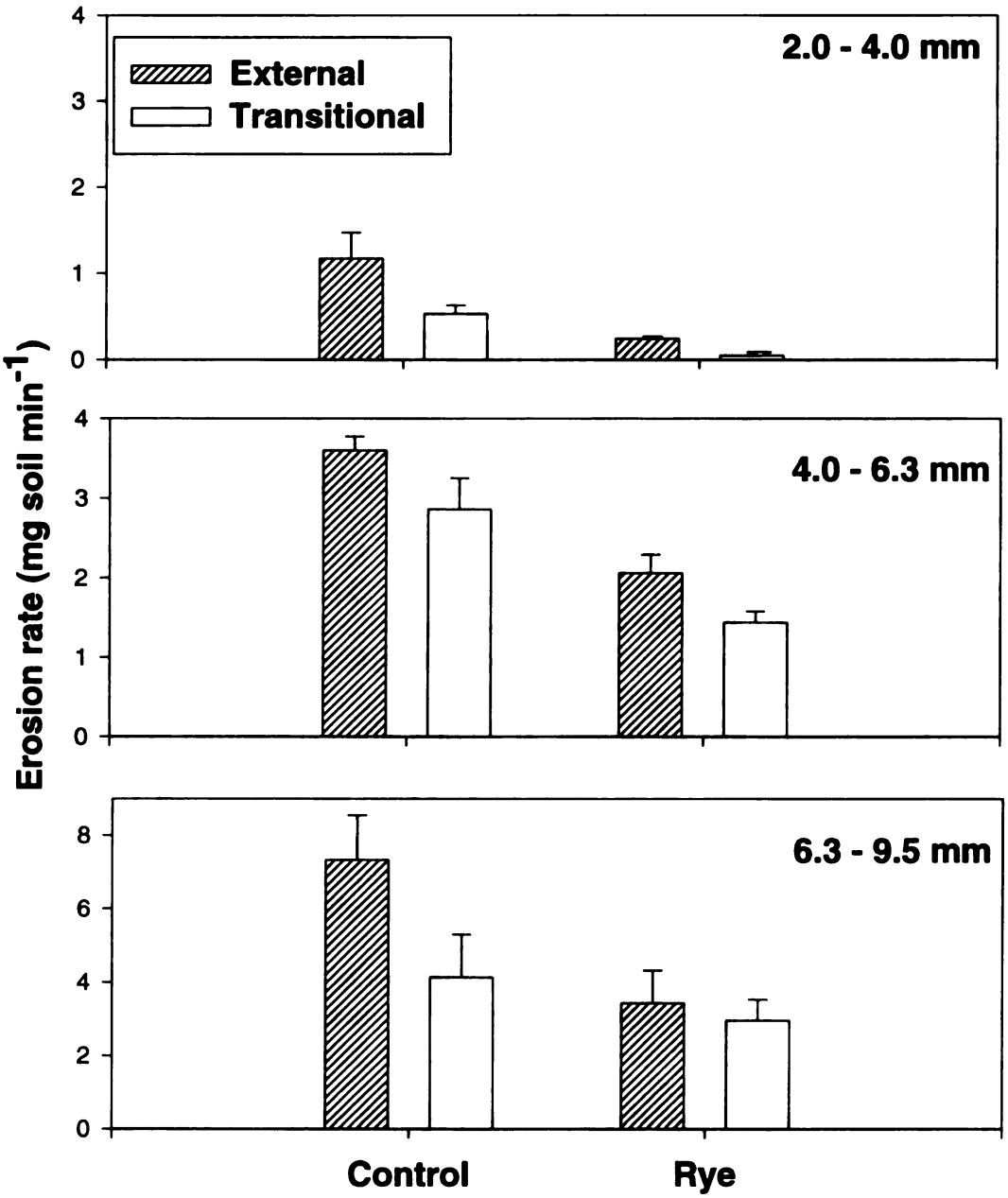

Figure 3.12 . Erosion rates of external and transitional layers of 2.0-4.0, 4.0-6.3 and 6.3-9.5 mm aggregates from no-rye (control) and rye cover cropped treatments of the Kalamazoo loam soil on October 1998 . Bars represent standard errors for n=4.

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CHAPTER 4

COVER CROP ROOT AND SHOOT NITROGEN CONTRIBUTIONS TO SUCCEEDING CORN CROP *IN SITU*

ABSTRACT

Winter rye (*Secale cereale*) cover cropping can reduce nitrogen leaching from the soil profile and serve as a nitrogen source for a succeeding crop of corn (*Zea mays,* L.). A field study was conducted on Kalamazoo loam soil (coarse-loamy, mixed, mesic Typic Hapludalf) to quantify N absorption by a living and resultant contributions of decomposing rye root and shoot residues through soil N pools and into corn.

Two open-ended PVC cylinder lysimeters were inserted through the Ap and into the center of the Bt_2 horizons. Rye cover crops in these cylinders were labeled *in situ* with ^{15}N by foliar applications of solutions containing $(^{15}NH_4)_2SO_4$ (%99 atom % ^{15}N). Corn was planted into the cylinders after herbicide desiccation of rye.

The average two-year recovery of rye root-derived ^{15}N by a successive corn crop was 13%. Recovery of rye shoot-derived ^{15}N by corn for two years averaged 8%. During the two-year study rye roots contributed nearly 12 kg N ha^{-1} to the succeeding corn crop and rye shoots contributed nearly 4 kg N ha^{-1} N to succeeding corn crops. Rye roots plus shoots contributed slightly more than 15 kg N ha^{-1} during the two-year study. Rye root N contributions were three-fold

greater than shoot N, supporting the importance of considering root contributions by a cover crop when developing N balance summaries for cover crop and successive cash crop rotations.

INTRODUCTION

Conservation tillage systems that leave crop residues on the soil surface are becoming very popular. The use of cover crop with a conservation tillage system can increase ground residue cover, reduce soil erosion, increase water infiltration, conserve soil water content and also serve as a sink source for plant nutrients. Rye (*Secale cereale, L.)* is regarded as one of the best suited crops for winter cover use because of its adaptability, tolerance to extreme cold and ease of establishments. Rye produces large amounts of mulch for succeeding no till corn (Ditsch et al., 1993). A better understanding of the processes involved in crop residue decomposition and N release in these systems is needed to develop more efficient residue and fertility management practices. Crop residues contribute significant amounts of N to the succeeding crop. Throughout the past decade, a large number of researchers have focused on winter rye cover crop uptake on residual soil N, release of N from cover crop residue (Ranells and Wagger 1997, Wagger 1989a), and N uptake by a summer crop (Karlen and Doran, 1991, Wagger 1989b). However, there is still lack of information on quantities of N contributed from above and below ground rye cover crop residues to succeeding corn plants. Plant roots control the concentrations and fluxes of

soil N by absorbing soil water and soluble N compounds (Frensch, 1996). Released N *in situ* from decomposing plant roots and shoots contribute N to the succeeding plant (Seiter and Horwath, 1999). Amount of N deposited in the rhizosphere of wheat accounted up to 20% of total plant N (Janzen, 1990 and Janzen and Bruinsma, 1993). The amount of N deposited from pea residue was 48% of belowground N and from barley was 71% of total belowground N at maturity (Jensen, 1996). Excretion of plant available N forms and mineralized forms of N from rhizodeposits may be reabsorbed by current or succeeding plants.

Most studies on ^{15}N labeled residue-decomposition and associated nitrogen transferred to the following crop have used dried leaves, stems and sometimes roots. Although some researchers have determined N uptake from root residues by succeeding plants, they first extracted roots from pots or microplots and then incorporated them into the soil (Harris and Hesterman, 1990, and Norman et al, 1990). Hubbard and Jordan (1996) reported ^{15}N recovery of corn from labeled soil plus a wheat root mix but they could not identify the direct recovery from roots only. Stevenson et al., (1998) used an indirect approach for estimating legume root-derived N uptake by succeeding plants. Few studies used *in situ* labeling of plant materials such as foliar N fertilization in field studies (Zebarth et al. 1991, Jordan et al., 1996) to determine plant uptake of N from foliar N fertilization. Seiter and Horwath (1999) best approached the question of root N contributions to successive plants by injecting ^{15}N into trees of agroforestry cultures and determined the corn uptake of root-derived N.

This research was conducted to specifically identify N contributions by aboveground and belowground residues of rye cover crops to succeeding corn plants using ^{15}N tracers under field conditions. The objective of this study was to determine recovery of N from rye roots and shoots by the succeeding corn crop.

MATERIALS AND METHODS

A two-year, field experiment was conducted from 1997 to 1999 on 16 Microplots (6 by 10 m) established in August 1994 by Rasse (1997) on a Kalamazoo loam soil (coarse-loamy, mixed, mesic Typic Hapludalf) at the KBS/LTER site in southwestern Michigan. The same four treatment, consisting of a control (C), rye roots only (RR), rye shoots only (RS) and rye roots and shoot mulch (RRS) were distributed in a randomized block experiment as was explained in previous Chapters. Some of the soil horizon properties and weather data for the experiment site are presented in Tables 4.1 and 4.2.

Experiments with ^{15}N

Two open-ended PVC cylinders, 30 cm in diameter and 60 cm in depth, were pushed through the Ap horizon and into the center of the Bt_2 horizon in each plot by the help of front fork loader of a tractor as explained in Chapter 2 (Kavdir, 2000). In spring and fall of 1998, approximately 45 rye seeds were planted into each cylinder of the rye treatment plots. The soil surface in each cylinder was covered with plastic sealed around the walls and each row by nontoxic clay sealant. Pine wood shavings were placed on the plastic to absorb ^{15}N labeled spray mist materials preventing them to contact with soil surface. Cylinders with no cover crops also covered plastic cover and pine shavings to receive the same treatments.

Rye plants were labeled with ^{15}N by means of foliar applications of solutions containing 6.39 g $(^{15}NH_4)_2SO_4$ containing 99 atom% ^{15}N dissolved in 9 L of distilled water in May. Three or four split applications of this solution were applied to prevent run off or leaf damage by toxicity. Each time equal amounts of ^{15}N solution (approximately 125 ml) were applied to each rye planted chambers manually using graduated fine mist spray bottles. Plants within the PVC were covered by clothes-baskets, with nested sides, and securely anchored to the soil at night or before rain events to prevent foliar losses. These covers were removed during sunny days.

Following a two week translocation period, the rye plants were spray-killed with 2% Roundup (glyphosate) Ultra, without ammonium sulphate, in early May of 1998 and 1999. Rye shoots were cut at the soil surface, wood shavings were vacuumed and the clay sealants and plastic soil covers removed from each ^{15}N lysimeter. Biomass samples of harvested rye shoots were weighed and subsampled for analyses. Rye shoots were placed on the soil surfaces inside the PVC cylinder lysimeters for all RS and RRS treatments.

Corn seeds (6-8) were hand planted into each PVC cylinder. Metal screens with 1 cm openings were placed on top of the soil and secured with nails to prevent residue loss by wind or animal consumption of corn seeds or rye shoots. Each chamber received 500 ml water from the soil surface. Chambers were thinned to two plants 2 days after emergence. Thinned corn plants were left on the soil surface of the chambers. No N fertilizers were applied to PVC lysimeters.

In the first year of experiment two corn plants were grown in each ^{15}N lysimeter. However, one of these plants was always smaller than the other one and showed weak growth. Therefore, during the second year one corn plant was grown in each ^{15}N lysimeter.

Soil sampling and analyses

Soil sub samples were taken before ^{15}N labeling and at harvest to determine initial and final ^{15}N contents of the soil. At harvest, September 1998, surfaces of the soil were divided into four equal parts: one part was taken for soil analyses and another part was taken for root extractions, using a square shovel. The remaining two parts were left in the chambers. During the second year, soil core samples were taken from the chambers to depths of 150 cm, using a hydraulic Gidding's probe (Giddings Machines Co., Ft. Collins, CO) to measure soil and corn root N and ^{15}N. Soil samples were split in half, vertically. One half was air dried, ground and sieved through 53 um screen. Samples smaller than 53 um size were collected and analyzed for total N and C by means of the dry combustion technique using a CHN analyzer (Carlo Erba, Italy) and $\%^{15}N$ by using Isotope Ratio Mass Spectrometer Model 2020 (Europa Scientific, Crewe, UK).

Rye and corn root and shoot sampling and analyses

Rye root and shoot sub samples were taken before and after the ^{15}N labeling to determine initial and final ^{15}N contents of plant shoots and roots. Soil core samples were taken from the top 15 cm depth of soil by pressing PVC tubing (117 cm^3) into the soil to sample rye roots before and after ^{15}N application. This soil was mixed with distilled water and the slurry poured through a 53 um screen, which retained the roots, which were washed with water. Fine white roots and plant residues were picked from the sand, which remained on the screen, using a tweezers. Fresh root biomass was recorded and calculated for each chamber. Both roots and shoots were oven dried at 70°C for 24 h. Corn roots were extracted from the soil matrix by sieving soil through a 1 mm screen washed by distilled water before drying.

At harvest, corn plants were cut 1 cm above soil surface and separated into ears, leaves and stems. Each plant part was weighed separately, dried and reweighed before grinding to pass through a 0.5 mm sieve. Ground samples were thoroughly mixed before 5-7 mg subsamples, weighed to 5 decimal places, were transferred into small tin capsules and placed into the autosampler. Total C and N were determined by the dry combustion method (Kirsten, 1983) using a C/N/S analyzer, NA 1500 series 2 (Carlo Erba Stumentazione, Milano, Italy) and $\%^{15}N$ using Isotope Ratio Mass Spectrometer Model 2020 (Europa Scientific, Crewe, UK).

Calculations

N derived from labeled residue (concentrations)

$$(\%Ndfr)=\frac{\text{atom \% 15N excess}_{\text{corn plant}}}{\text{atom \% 15N excess}_{\text{labeled rye root or shoot}}} \times 100 \quad [1]$$

where:

Atom $\%^{15}N$ excess of corn (ear, leaf, stem or root) =
(atom ^{15}N of corn grown in labeled soil) – (atom ^{15N} of corn grown in unlabelled control)

Atom $\%^{15}N$ excess of rye root and/or shoot =
(atom ^{15}N of labeled plants) – (atom ^{15N} of plants before labeling)

Recovery of ^{15}N from rye roots and/or shoots = [2]

$$\frac{\%\ \text{Ndfr} / 100\ \text{X N content of succeeding corn}}{\text{N return from rye shoots and/or roots}}$$

N_{dfr} kg ha^{-1}= % Ndfr x N accumulation in succeeding corn plant [3]

where:

The N accumulated (kg N ha^{-1}) in ear, leave, stem and total corn plant from labeled rye shoots and/or roots are equal to % Ndfr times %N of corn times the biomass (kg) of corn per ha.

Calculations were modified from Stevenson et al. (1998).

Statistical analyses

Treatment effects on %Ndfr, $\%^{15}N$ recovery and kgNdfr ha^{-1} were estimated by a PROC-GLM (ANOVA) procedure using Statistical Analysis System (SAS Institute, 1999). Fisher's LSD test was used to separate means of measurements. Correlation analyses were used to determine relationship between plant and soil parameters. All significant tests were set at the 0.05 level.

RESULTS AND DISCUSSIONS

Corn N recovery from rye shoots

Recovery of rye shoot-derived ^{15}N by above and belowground parts of the corn plant was 8.6% (17.2% for 2 corn) in 1998 and 7.6% in 1999 (Figures 4.1 and 4.2). Partitioning of total recovered rye shoot derived N in various parts of corn showed that 24.3 to 48.1% was translocated to the ears (Figures 4.3 and 4.4). Corn was more mature at harvest in1999 and resulted the greater recovery of ^{15}N by the corn ears than the other plant parts. Corn roots had the lowest ^{15}N recovery, 4 % and 2.6 % in 1998 and 1999, from rye shoot-derived ^{15}N (Figures 4.1 and 4.2).

Corn N recovery from rye roots

Recovery of rye root-derived ^{15}N by the entire corn plant was 11.2% in 1998 and 14.7% in 1999 (Figures 4.1 and 4.2), which was higher than that recovered from rye shoots. Recovery of rye root derived ^{15}N by 2 corn plants in 1998 was 22.4%. Corn ears recovered the greatest amount of ^{15}N from rye roots, 53.4 % in 1998 and 51.4 % in 1999 of total recovered N by whole corn plant (Figures 4.3 and 4.4). Stevenson et al.(1998), reported 2 to 4% recovered from wheat residues and 3 to 5% of ^{15}N were recovered from pea residues. They suggested that crop roots were also very important N contributors to soil N pools and should not be ignored when modeling soil N.

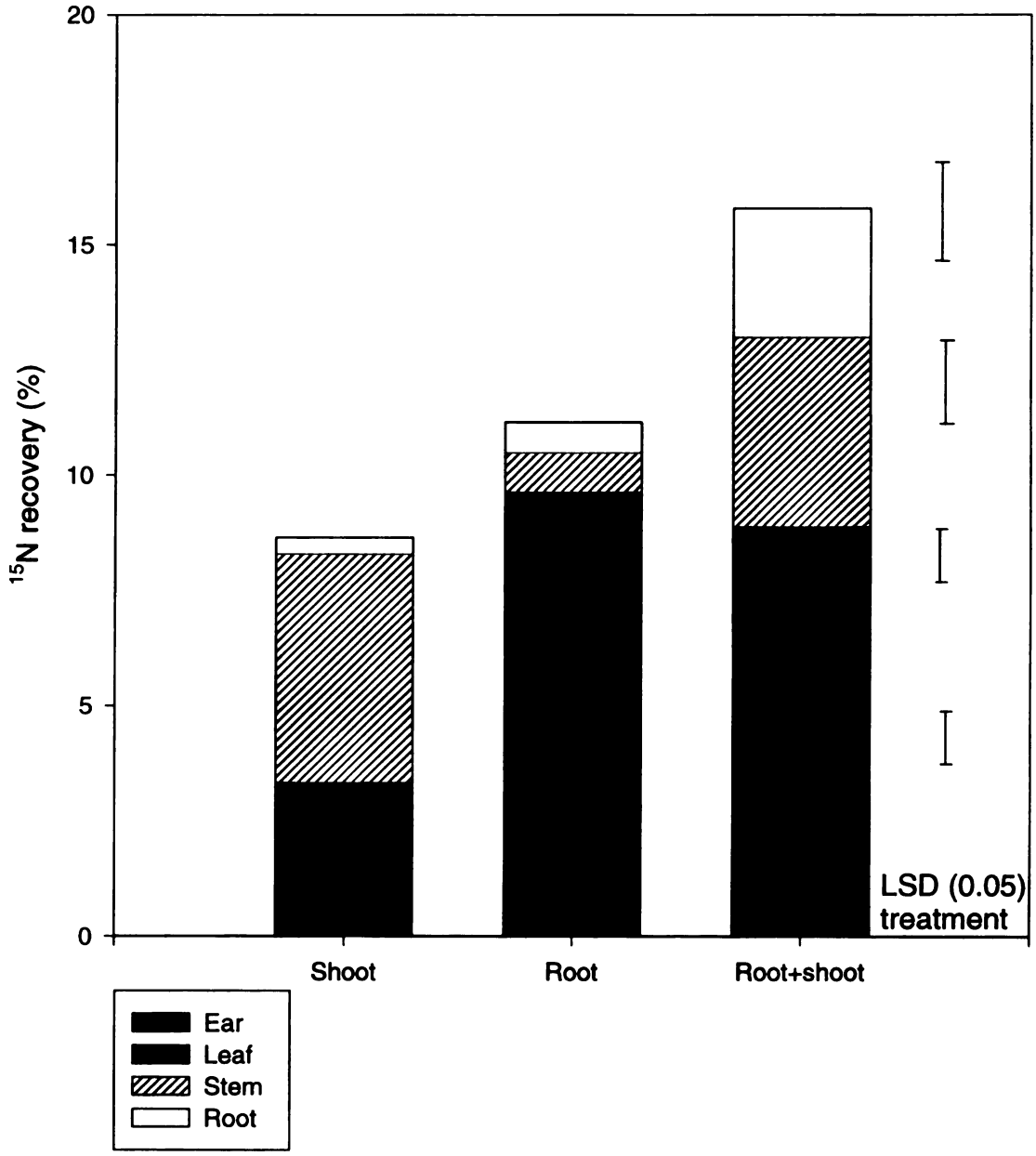

Figure 4.1. Percentage of ^{15}N recovered from rye shoots, roots and roots+shoots by corn ear, leaf, stem and root at harvest in 1998, n=4.

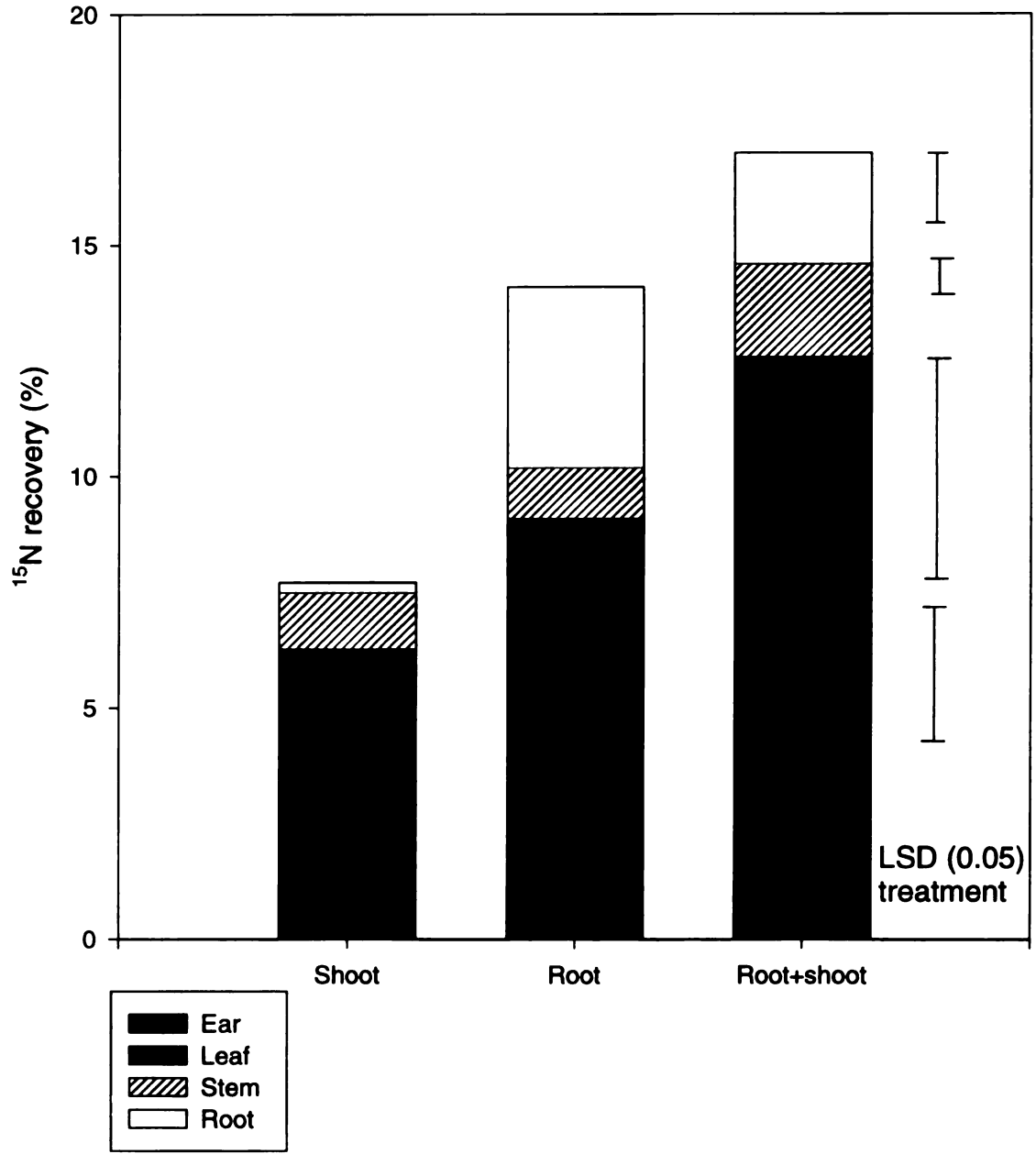

Figure 4.2. Percentage of ^{15}N recovered from rye shoots, roots and roots+shoots by corn ear, leaf, stem and root at harvest in 1999, n=4.

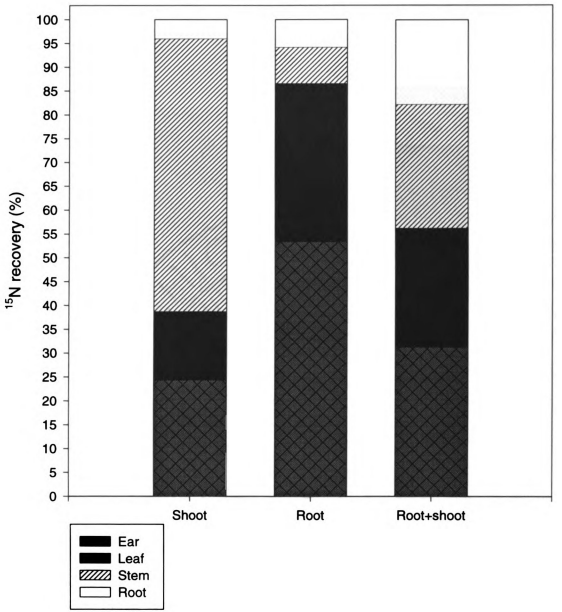

Figure 4.3. Partitioning of total recovered N from rye shoots, roots and roots+shoots by corn ear, leaf, stem and root at harvest in 1998, n=4.

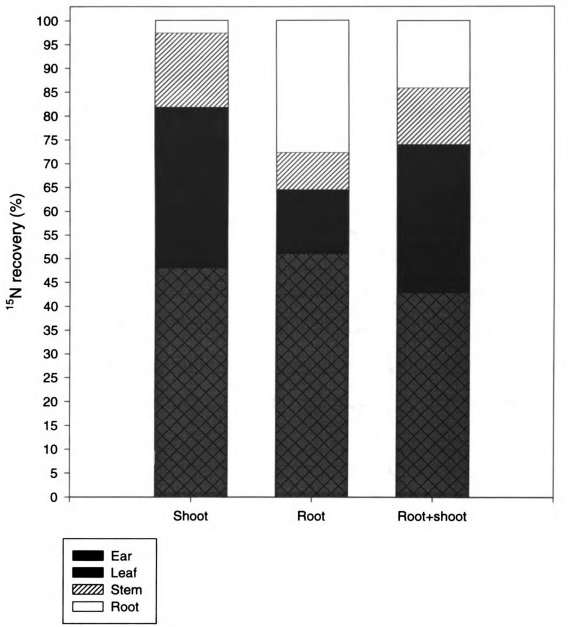

Figure 4.4. Partitioning of total recovered N from rye shoots, roots and roots+shoots by corn ear, leaf, stem and root at harvest in 1999, n=4.

When they used indirect approach, ^{15}N labeled fertilizer and non labeled residue application, recovery of ^{15}N by wheat from pea residues increased up to 11%. This increase was due to root derived nitrogen to the soil N pool. In our study, using the direct approach (^{15}N labeled residue) was used and gave us a better tool to determine root N contributions to the successive corn plants. Utilization of N derived from rye roots by corn was significantly greater than for rye shoots ($p<0.05$). Similar results were found for N derived from shoots and roots of wheat by Thomsen et al. (1996). They reported that decomposition and ^{15}N mineralization of wheat roots were faster and the uptake of wheat root derived ^{15}N was greater than ^{15}N from wheat shoots. Similarly in our research, earlier mineralization of ^{15}N resulted in more ^{15}N recovery by corn plant from rye roots. In a previous Chapter 3, it was reported that N derived from rye roots was greater than N derived from rye shoots in the exterior layer in June 1998 (Kavdir, 2000). It was also reported that there was a direct relationship between changes in the ratio of total N of external layers and internal regions of soil aggregates and corn biomass from the beginning to the end of corn growing season. Rye root N contents in PVC ^{15}N lysimeters had an average value of 57.5 kg N ha^{-1} while shoot N content in PVC chambers had 58.7 kg N ha^{-1} in 1999. Therefore, it can be concluded that rye roots conserve as much N as rye shoots. However, the contributions of rye root-derived N to the succeeding corn was six times greater in 1998 and twice as much as from rye shoots in 1999 (Table 4.3).

Table 4.1. Thickness, pH and bulk density of Ap, Bt_1 and Bt_2 horizons at LTER Microplots at Kellogg Biological Station, MI.

Horizon	Depth cm	pH†	Bulk Density g cm^{-3}
Ap	0-31	5.5	1.5
Bt_1	31-49	5.7	1.7
Bt_2	49-65	5.3	1.8

†Data were taken from KBS-LTER web site, www.kbs.msu.edu

Table 4.2. Weather data for 1998 and 1999 of LTER Microplots at Kellogg Biological Station, MI.

Year	†Precipitation (mm)	*Yearly Mean Air Temp (C)	*Yearly Max Air Temp (C)	*Minimum Air Temp
1998	812.3	10.7	34.2	-16.5
1999	624.2	11.1	35.5	-24.3

†Data were taken from KBS-LTER web site, www.kbs.msu.edu

Table 4.3. Contributions of rye shoot, root and root+shoot to corn N contents in 1998 and 1999 at LTER Microplots of a Kalamazoo loam, n=4.

Treatment	1998			
	Ear	**Leaf**	**Stem**	**Total**
	kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}
Shoot	0.58b†	0.36b	1.47b	2.41b
Root	6.79a	4.33a	3.89a	15.01a
Root+shoot	6.50a	4.85a	4.15a	15.50a
	1999			
Treatment	**Ear**	**Leaf**	**Stem**	**Total**
	kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}
Shoot	2.42b	1.51a	0.91a	4.84a
Root	5.78a	1.76a	0.78a	8.32a
Root+shoot	6.78a	5.90a	2.09a	14.76a

†Values followed by the same letter within same column (in each year) and between treatments are not significantly different at $p>0.05$ according to Fisher's LSD.

Residue and soil contact are important considerations for the best decomposition of plant material as well as the quality of plant material. Schomberg et al.(1994) reported that decomposition rate of incorporated residues into the soil was faster when they were placed on the soil surface. Thus continuous contact of root residues with soil particles in contrast to surface placed rye shoot residues caused much faster decomposition of dead rye roots despite of greater C:N ratios of root residues (Kavdir, 2000, Chapter 3). Rye root and shoot N values in ^{15}N lysimeters were approximately 2 times greater than those for the outside of the chambers due to greater population of rye in chambers. We can conclude that corn utilized rye root-derived N more than rye shoot derived N due to early mineralization of roots. The retention of rye derived N was retained primarily on exterior layers of soil aggregates causing rye N to become much more available for growing corn roots (Kavdir, 2000, Chapter 3)

Root plugging of some of the macropores also reduced leaching of mineralized N and more ^{15}N was retained on the surfaces of aggregates (Chapters 2 and 3). In Chapter 3, (Kavdir, 2000) it was reported that contributions of rye root-derived N were greater than that of rye shoot-derived N to the soil aggregates. Both concentration and gradient of recently derived rye N increased with increasing aggregate sizes. In both years recovery from the plots where rye roots were present was greater than the only shoot applied plots.

There was a direct linear correlation (r^2=0.68) observed between ^{15}N ratio of exterior layers to interior regions of soil aggregates and ^{15}N uptake by corn

plant (Kavdir, 2000 ,Chapter 3). Recovery rates of ^{15}N from rye roots plus shoots were the highest in both years (Figures 4.1 and 4.2). Corn above and belowground parts recovered 15.8% and 17.0% of rye root plus shoot derived ^{15}N in 1998 and 1999 respectively.

Harris and Hesterman (1990) reported corn recovery of N from alfalfa was 29% for root-derived N and 21% for shoot-derived N. Compared to rye, recoveries of N from alfalfa shoots and roots by corn were greater. However, contributions of rye roots to the retention of N and timely release of this N to succeeding corn crop can not be overlooked.

Retention and loss of rye root and shoot derived N from soil

Soil retained 40, 62 and 61% of rye shoot, root and root plus shoot-derived N in 1998. Recovery of N from shoots, roots, and root plus shoots of rye by soil were 21, 60 and 70 % respectively in 1999 (Figures 4.5 and 4.6). Unaccounted portions of ^{15}N in treatments with labeled shoots and roots were assumed to be lost from the soil by leaching. Plots with rye shoots applications to bare soil lost 42% of the rye shoot-derived ^{15}N in 1998 and 70% of the rye shoot-derived ^{15}N in 1999 from the soil profiles (Figures 4.5 and 4.6).

Hubbard and Jordan (1996) observed greater ^{15}N losses from labeled wheat roots and soil when wheat shoot residues were placed on the soil surface. Leaching and some denitrification of N could be the reason for greater N loss from rye shoot mulching of surface soils. Application of surface placed plant mulches decreases raindrop effects, reduces evaporation and increases

saturated hydraulic conductivity. Saturated hydraulic conductivities of soils increased four-fold when applications of rice straw mulches to the soil surface were increased from 0 to 12 Mg ha^{-1} (Lal et al., 1980).

Rasse (1997) reported that denitrification rates were higher when alfalfa shoots were applied to bare soil than when alfalfa was planted in Microplots at KBS. Alfalfa shoot applications to bare soils increased denitrification losses by nearly 250 g N $(ha\ d)^{-1}$. Denitrification losses were not measured in this study.

Nitrogen isotope quantities remaining in the rye shoot residues, at the end of the corn harvest, were very low (Figures 4.5 and 4.6). One of the reasons behind the low ^{15}N in the remaining residue may be due to uncontrolled conditions in the field experiments such as soil disturbance by animals and weather conditions. Once corn crop reached to certain growth size, metal nets on the soil surfaces were removed to obtain better corn growth. Thus the residue biomass covered at the end of the experiment may have been smaller than the actual amounts added.

Total N (kg N ha^{-1}) recovered from rye residues were calculated by using the equation [3]. Recovery of N was 2.41, 15.01 and 15.50 kg N ha^{-1} in 1998 and 4.84, 8.32 and 14.76 kg N ha^{-1} in 1999 from shoots, roots and root plus shoots of rye (Table 4.3). These similar quantities of 15 kg N ha^{-1} for both years confirms that substantial contributions of N are absorbed by a winter rye cover crop and passed along to successive corn production.

We can conclude that rye cover crop shoots and roots supplied 15.50 kg N ha^{-1} to the succeeding corn plants under limited N conditions of a Kalamazoo

loam soil. Contributions of rye root-derived N was greater than that of rye shoot-derived N to the succeeding corn plant. Most of the rye-derived N, absorbed by corn, was distributed primarily to the ears with descending quantities deposited in the leaves, stems and roots. Rye root contributed to N to the succeeding corn plant by reducing N leaching from the soil profile and releasing N via root exudates and mineralized N from dead roots. Therefore active plant roots should be maintained between two successive cash cropping to maximize soil N availability and reducing N leaching.

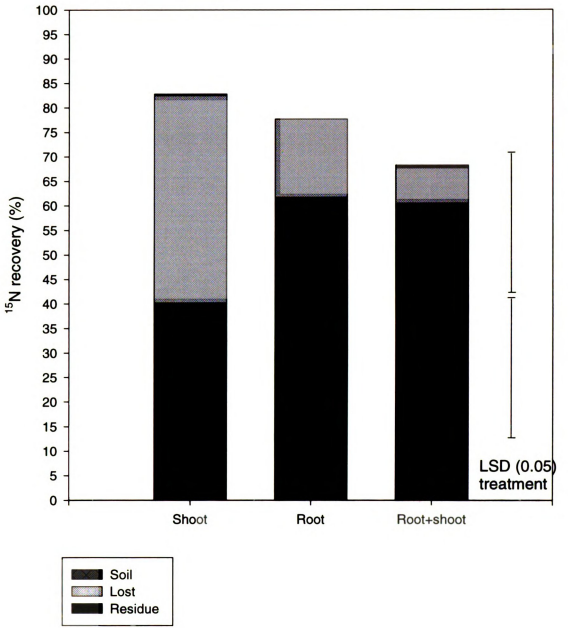

Figure 4.5. Percentage of ^{15}N from rye shoots, roots and roots+shoots retained by soil, ^{15}N remained in residue and lost from lysimeter soil profile of a Kalamazoo loam soil at harvest in 1998, n=4.

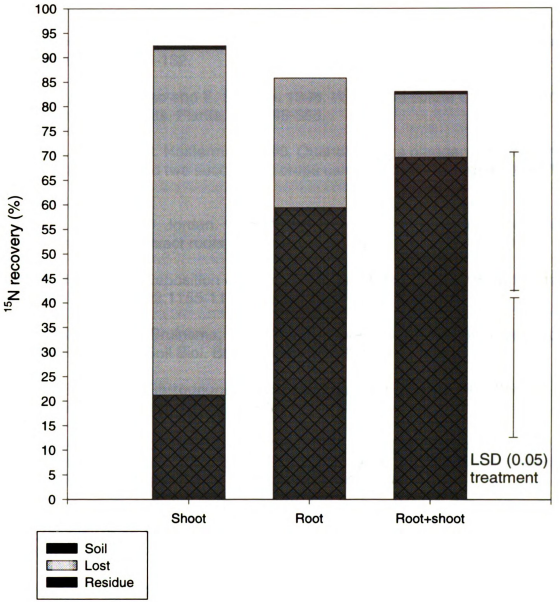

Figure 4.6. Percentage of ^{15}N from rye shoots, roots and roots+shoot retained by soil, ^{15}N remained in residue and lost from lysimeter soil profile of a Kalamazoo loam soil at harvest in 1999, n=4.

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SUMMARY AND CONCLUSIONS

Rye cover crop reduced inorganic N leaching from corn-based agroecosystems, during a two-year field study. Rye roots recovered and retained greater quantities of N than rye shoots reduced N leaching from the soil profile. Soil tillage also influenced the amount of inorganic N lost below the rooting zone of a Kalamazoo loam soil.

Two-stage applications of Roundup herbicides to Roundup ready corn grown in NT systems successfully reduced N leaching during a wet year. After band spraying of rye, living rye roots between rows reduced soil nitrate leaching by plugging some of the soil macropores and absorbing soil nitrates in both N fertilized and non-fertilized plots. Strategic band placement of herbicide provided a slow-release, during plant decomposition, of a rye-based starter N while N absorption by the standing rye cover crop continued across more than 65% of the soil surface between the young corn rows.

Negative correlations were observed between inorganic N contained in soils and associated root lengths, volumes and surface areas in Ap horizons of all treatments. These negative correlations appeared to result from the greater root populations and more efficient N uptake by rye roots. Nearly 90 and 40 kg ha^{-1} in CT-F and NT-F were retained in soil profiles due primarily to the plugging of soil pores by roots. Therefore, using two-stage herbicide applications in NT management systems, kept as many active rye roots as possible in the soil and

reduced N leaching while retaining more N in the soil profile for the succeeding corn crop.

Incorporation of rye into soil by tillage resulted in possible breakdown of soil aggregates. Nitrogen in the centers of large soil aggregates became more available for N mineralization and to the succeeding corn plants. Regardless of greater N leaching from CT treatments, greater corn yields were observed in CT than NT treatments. Presence of rye did not significantly increase or decrease corn grain yields. A direct linear correlation ($P<0.05$) between rye biomass N content and grain yield $r^2=0.75$ in 1998 and $r^2=0.75$ in 1999 was observed for all non-fertilized and rye cover planted plots. Under non-N fertilized conditions, additions of N via rye cover crop roots and shoots mineralization increased corn grain yields.

Rye cover crop root contributions to the reduction of N leaching has been underestimated by most of the researchers. Results from these studies indicated that surface area, volume and length of rye root were much more important factors than rye root biomass to uptake N from the soil profile. These greater morphological root parameters are indicators of greater root plugging and absorption than is root biomass. Rye roots also contribute to the stabilities of external concentric layers of soil aggregates ranging in size from 2.0-9.5 mm across.

Separating individual soil aggregates into three different layers by SAE chambers greatly increased the sensitivity of identifying ^{15}N dynamics within soil aggregates and associated measurements of short term contributions of cover

crop N and C in soil aggregates and their concomitant effects on plant N nutrition. Soil aggregates from rye cover crop treatments were much more resistant to erosion forces to the external and transitional concentric layers than soil aggregates from no rye cover crop treatments. Soil eroded from external and transitional layers of soil aggregates layers was reduced from 2-10 fold by rye cover crop. Smaller soil (2.0-4.0 mm) aggregates were much more resistant to erosion than larger (6.3–9.5) mm across aggregates. Transitional layers of soil aggregates were more resistant to erosion than exterior layers of soil aggregates.

Rye root and shoot derived nitrogen had accumulated on the exterior layers of soil aggregates 4.0 to 6.3 mm and 6.3 to 9.5 mm across, 17 days after rye shoots were application to the soil surface. Greater root-derived N accumulated on the exterior layers of soil aggregates. Rye roots contributed more N to the soil aggregate surface layers than did rye shoots. Gradients of recently derived rye N increased with aggregate sizes. These results supported that roots grow preferentially around the surfaces of soil aggregates, through associated macropores, rather than through the internal regions of soil aggregates. Organic materials derived from rye roots and shoots were homogeneously distributed across soil aggregates 2.0-4.0 mm across resulting in minimum ^{15}N gradients within smaller aggregates.

High correlations were discovered between changes in the ratios of total N contents in external layers and internal regions of soil aggregates and the production of corn biomass from the beginning to the end of corn growing season. More positive ratios produced greater corn biomass. Thus, it is clear that

uptake of N is more efficient from the surfaces of the soil aggregates larger than 4 mm.

Concentric gradients of total N were found for soil aggregates larger than 4 mm. These gradients appeared to develop following the formation of soil aggregates. Concentric gradients of rye root and shoot derived N increased with increasing aggregate size and changed with time. The location of N in a soil aggregate was important for corn plant utilization. There seemed to be a constant rate of migration or flux of ^{15}N ions, mostly organic in nature, originating from rye roots and shoots into soil aggregates. Early in the season, more ^{15}N migrated to the interior regions of the smallest aggregates, 2–4 mm across, but was limited to only surface and transitional layers of the larger aggregates, 6.3–9.3 mm across. At harvest, more of the ^{15}N located within interior regions of the smallest sized aggregates had been withdrawn by corn root activity while more ^{15}N remained within the interior regions of the medium to larger sized soil aggregates 4–6.3 mm across. These ^{15}N gradients suggested that the preformation and of soil macroaggregates and functional fluxes of N are very dynamic processes utilizing many biogeochemical reactions. Therefore, the soil aggregate hierarchy model, proposed by Oades and Waters (1991) cannot be the only model for the formation of soil structure within a Kalamazoo loam soil. If this were the only model of aggregate formation then macroaggregates and microaggregates would exhibit similar N gradients as the smaller aggregates would obtain the uniform N concentrations before aggregating into larger hierarchies of larger aggregates. These larger aggregates should contain similar concentrations of N throughout.

In contrast, we identified concentration gradients of plant-derived N across soil aggregates greater than 4 mm. The location of the N, especially on soil aggregate surface layers, highly contributed to N uptake by the contemporary corn crop. Rye root and shoot derived N, located within exterior layers of larger soil aggregates decrease with time with corn root uptake of N. Average recovery of rye root ^{15}N by above and belowground parts of the corn plant was 13 %. Recovery of rye shoot derived ^{15}N by above and belowground parts of corn was 8 % (average of two year). Therefore these studies clearly demonstrate that active reduce N leaching from the soil and the strategic management of rye cover crops deposit highly available N to soil aggregate surfaces which is preferentially absorbed by roots of a successive corn crop.