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ALFALFA AND CORN ROOT MODIFICATIONS OF SOIL NITROGEN FLUX AND RETENTION

By

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ABSTRACT

ALFALFA AND CORN ROOT MODIFICATIONS OF SOIL NITROGEN FLUX AND RETENTION

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Sustainable nitrogen-conservative agroecosystems are increasingly sought by agronomists and environmentalists. This study was designed to evaluate the global hypothesis that temporal continuity of root systems within the soil profile diminishes nitrate leaching and builds easily mineralizable nitrogen pools within root-zone soils. Effects of alfalfa root systems on soil physical properties, soil nitrogen leaching and corn nutrition were investigated in two separate experiments conducted on Kalamazoo loam soils (fine-loamy, mixed, mesic Typic Hapludalf) in southwestern Michigan from 1994 to 1996. In the first field experiment, soil nitrogen dynamics were compared under alfalfa and bare fallow. The second field experiment was conducted in conventional and no tillage plots under corn - alfalfa rotation equipped with undisturbed, *in situ*, large monolith lysimeters. Measurements in this study included: 1) soluble soil mineral nitrogen from suction lysimeters, and fixed soil mineral nitrogen from soil core extractions, 2) volumetric soil water contents by time domain reflectometry, 3) root biomass extracted from deep probe samples, 4) root demographics by minirhizotron technologies, 5) soil physical measurements, and 6) plant biomass and yields. The presence of alfalfa root systems significantly increased saturated

hydraulic conductivity, total, and macro-porosities of soils compared to bare fallow. Living alfalfa root systems efficiently prevented nitrate leaching throughout the year, by generally keeping soil solutions below 1 mg l^{-1} of NO_3-N. Second year alfalfa stands accumulated 26 and 76 kg N ha^{-1} in the crowns and roots, respectively. Decomposing alfalfa shoots had little impact on soil nitrate contents compared to root systems, but promoted greater nitrate leaching and denitrification rates. Mineral nitrogen released from spring spray-killed alfalfa and associated soil mineralization was estimated at 115 kg N ha^{-1}. Mineral nitrogen contents of fertilized plots averaged more than 200 kg N ha^{-1} in late November 1996. All nitrogen fertilizer applied to corn, planted directly after spray-killed alfalfa, remained in the soil as mineral nitrogen which was vulnerable to spring leaching. Corn root densities per soil horizon, planted after alfalfa, mimicked alfalfa root demographics. An excess of 40% of the corn roots recolonized alfalfa root induced macropores.

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INTRODUCTION

Nitrogen-conservative agricultural systems are increasingly sought by agronomists and environmentalists. Organic and mineral nitrogen pools have to be contained in the upper regions of the soil profile in order to: (1) maximize N availability to crops, (2) minimize NO_3 leaching losses to groundwater, (3) minimize N_2O gaseous losses involved in the greenhouse effect (Peterson and Russelle, 1991). In the American corn belt alfalfa dinitrogen fixation contributes to N inputs of more than 1 billion kg N yr^{-1} (Peterson and Russelle, 1991). Consequently, alfalfa is the most important perennial legume in rotation with corn in the north central states (Eberlein et al., 1992). Mineralized nitrogen from alfalfa plants covers most to all nitrogen requirements of the succeeding corn crop (Baldock and Musgrave, 1980; Bolton et al., 1976; Bruulsema and Christie, 1987; Fox and Piekielek, 1988; Hesterman et al., 1986a). Though little nitrate leaching has been reported under living alfalfa stands (Peterson and Russelle, 1991; Owens, 1990), substantial N losses by deep leaching were observed in soils following plowed down alfalfa stands. Deep leaching of NO_3-N has also been associated with inappropriate practices such as killing the alfalfa stand in the Fall (Cambell et al., 1994; Robbins and Carter, 1980). Consequently, best management practices for alfalfa, in rotation with corn, require the maximum absorption of alfalfa-generated N by corn in order to minimize nitrate leaching.

Alfalfa crops are generally plowed down with substantial amounts of above-ground plant material (Baldock and Musgrave, 1980; Robbins and Carter, 1980). Several authors have reported total N contents of alfalfa shoots, crowns and roots and the time of plowing (Bruulsema and Christie, 1987; Lory et al., 1992b). Nevertheless, little is known about the specific contributions of alfalfa above- and below-ground biomass to soil N fluxes (leaching and denitrification) and retention (organic and mineral N pools). The first general objective of this research is to identify and quantify nitrogen pathways in a Kalamazoo stratified loam (fine-loamy, mixed, mesic Typic Hapludalf) under alfalfa and bare fallow. The corresponding general hypothesis is that alfalfa root systems contribute more than shoots to N retention in the upper regions of the soil profile. The following hypotheses are associated with this main hypothesis:

1.1. Living alfalfa root systems greatly reduces leaching of mineral nitrogen released by the mineralization of soil organic matter and decomposition of alfalfa shoots compared to bare fallow.

1.1.1. Application of alfalfa shoot mulch increase alfalfa herbage yields because alfalfa roots efficiently absorb supplemental nitrogen inputs.

1.2. Crowns and roots of alfalfa contain greater quantities of nitrogen than alfalfa shoots after two growing seasons.

1.3. Soil organic matter contents are increased by alfalfa root systems compared to bare fallow, but not modified by alfalfa shoot mulch application to bare fallow or alfalfa stands.

1.4. Application of alfalfa mulch to bare soil fallow does not contribute to sustained increases of mineral nitrogen in the soil profile because of greater leaching and denitrification losses.

Part of the rotation effect of legumes to successive crops has been attributed to improved soil physical properties (Folorunso et al., 1992; McVay et al., 1989). Though this improvement results from a combination of effects from the above and below ground plant material, few studies have identified their specific contributions. The second main objective of this study is to compare early changes in soil physical properties under alfalfa stands and bare soil fallow. The corresponding general hypothesis is that alfalfa shoot and root materials modify certain soil physical properties. The following hypotheses are associated with this main hypothesis:

2.1. Alfalfa root system specifically increase saturated hydraulic conductivity and porosity of soils because of the network of root-induced macropores (RIMs) generated by alfalfa root system.

2.2. Decomposition of alfalfa shoots increases structural stability of surface soils to a greater extend than alfalfa root systems.

The third main objective of this research is to quantify and compare plant root systems and soil nitrogen pools within CT and NT soils in alfalfa and corn rotations. The corresponding general hypothesis is that most nitrogen requirements of corn, planted directly after killing a one-year alfalfa stand, are met by alfalfa and SOM mineralization products. The following hypotheses are associated with this main hypothesis:

3.1. Following one year of alfalfa, nitrogen fertilization does not improve corn yields.

3.2. Corn root distribution within the soil profile conforms to root distribution patterns of the preceding alfalfa root system, as corn roots proliferate into in N-enriched RIMs of the soil generated by the decaying alfalfa roots.

Alfalfa Nitrogen Fixation and Contents

Alfalfa dinitrogen fixation contributes to N inputs in the American corn belt for more than 1 billion kg N y^{-1} (Peterson and Russelle, 1991). Net production of soil nitrogen (i.e., soil N gain + plant uptake) by alfalfa has been reported to be greater than red clover and much greater than peas or vetch (Lyon and Bizzell, 1993). The improvement of the soil nitrogen status has mainly been attributed to the high dinitrogen fixation potential of alfalfa (Fox and Piekielek, 1988). Opposite to birdsfoot trefoil, alfalfa would principally release nitrogen by root decay rather than by the decomposition of the nodules (Dubach and Russelle, 1994). The direct excretion of nitrogen compounds (e.g., ammonia, glutamate, serine, alanine and aspartate) occurs mainly by the loss of recently fixed dinitrogen (Ta et al., 1986).

Peterson and Russelle (1991) estimate that dinitrogen fixation provides 50% in the seeding year and 80% in the second year of alfalfa nitrogen requirements. Their estimations of alfalfa dinitrogen fixation range from 70 for seedling stands to 400 kg N ha^{-1}. Most studies have reported that increased levels of soil mineral nitrogen diminish symbiotic fixation (Cherney and Duxbury, 1994; Phillips and DeJong, 1984). Others report that alfalfa presents the remarkable ability to continue symbiotic fixation at high soil mineral nitrogen levels (Lory et al 1992b, Lamb et al. 1995a).

The Alfalfa Root System

Alfalfa root system branches to a maximum of four orders (Weaver, 1926). Jones (1943) reports three overlapping concepts regarding alfalfa root system: transient vs. permanent, non-cambial vs. cambial, and primary vs. secondary development. The vast majority of the transient are non-cambial and primary, while the permanent are cambial and secondary. However, Jones (1943) indicates that often no external morphological characteristic distinguishes the two types. Roots that are several years old present large areas of secondary derived cells and a prominent woody axis (Grove and Carlson, 1972). Secondary thickening of fine roots is initiated by the cambium, nevertheless the majority of the fine roots will rarely develop cambiums, at least no complete phellogen, and

thus they appear unable to survive indefinitely (Jones, 1943). The turn over of the root system during the growing season and the winter is due to the growth and decay of these noncambial roots.

Alfalfa fine root development is optimal in the spring (Jones, 1943; Pietola and Smucker, 1995), then slows down during the summer to increase again in the fall (Jones, 1943). Fine root production is enhanced by sufficient precipitations (Pietola and Smucker, 1995). Though many studies have shown alfalfa defoliation induces substantial starch remobilization from the root system (Boyce and Volenec, 1992; Gramshaw et al., 1993; Pearce at al, 1969), fine root death does not seem to increase (Pietola and Smucker, 1995).

Over 70% of the alfalfa root biomass is concentrated in the upper 20 cm of the soil profile (Blumenthal and Russelle, 1996; Jodari-Karimi et al., 1983; Lory et al., 1992a; Sanderson and Jones, 1993) and appears to concentrate at greater depths with age and soil type (Bolton, 1962). Nevertheless, less than 10% of that biomass is composed of non secondarily thickened roots (Blumenthal and Russelle, 1996). Alfalfa rooting depths of 3 to 4 m are common, and 10 to 12 m have been recorded (Bolton, 1962). Pietola and Smucker (1995) observed maximum alfalfa root density at depths of 35 cm in year one and 55 cm in year two, and deeper than a meter from the third to the fifth year.

Root Systems Distribution and Recolonization

Distribution of root systems in the soil profile is an important factor in the determination of water and nutrient availability to plants (Kuchembuch and

Barber, 1987). Modified distributions of corn root systems within the soil profile have been observed under contrasted fertilizer (Anderson, 1987; Durieux et al., 1994), irrigation (Robertson et al., 1980), and tillage managements (Anderson, 1987; Bauder et al., 1985; Vepraskas and Wagger, 1990). Development of the corn root system is facilitated at depth where optimal conditions for water, nutrients and soil physical properties are met. The specific recolonization of root induced macropores by newly developing root systems has been suggested as an important factor influencing root growth and water movement through soils (Smucker et al., 1995). Root colonization of horizons has been reported to be in direct relationship with the number of soil biopores (Wang et al., 1986). Alfalfa (*Medicago sativa* L.) in rotation with corn has been reported to promote corn root distribution in the soil profile by creating accessible root induced macropores (RIMS) for corn root development (Stone et al., 1987). This mechanism certainly bears trophic implications. Plants reinstate substantial amounts of carbon and nitrogen to soils through root exudation and decay (Milchunas et al., 1985; Smucker, 1984). The colonization of recent RIMS and root growth along decaying root tissue can play a important role for plant nutrition in both rotation and intercropping systems. Carbon inputs from alfalfa root systems to soil were assessed to be five times higher than corn root contributions (Angers, 1992). During the growing season significant amounts of fixed nitrogen can be transferred from alfalfa to intercropped plants (Brophy et al., 1987; Ta and Faris, 1987). Consequently, root proximity to nutrient source, i.e. decaying root tissue, can play an important role in plant nutrition.

Mineralization of Soil Organic matter, and Alfalfa and Corn Plant Tissues

Soil organic matter (SOM) contents decrease under bare fallow soils due to mineralization processes (Barber, 1979; Larson et al, 1972). Barber (1979) estimates that 2.4% of bare fallow soil SOM is lost to mineralization, annually, from a Raub silt loam in Indiana. Broadbent and Nakashima (1974) report an SOM annual mineralization rate of 5 to 6%, in a five-year incubation study. Long-term studies are generally needed to show declines in SOM levels induced by cropping system or residue restitution. Collins et al. (1992) observed a decline from 1.20 to 1.05% SOM when wheat straw was burned rather than incorporated over a period of 58 years. Angers et al. (1995) observed a decline in soil carbon levels from 0.832% to 0.649% after 11 years of corn cultivation following the original plowing of an old pasture. Differences in SOM mineralization over the whole Ap horizons are often difficult to show in studies shorter than five years (Angers, 1992; Angers et al., 1992; Gupta et al., 1994). Angers (1992) observed no significant differences between alfalfa, corn and bare fallow soils after two years of treatment. After five years of treatment, soil carbon levels significantly decreased in bare fallow (-0.36 g kg^{-1} yr^{-1}) and corn plots (-0.24 g kg^{-1} yr^{-1}), while increasing in alfalfa plots (+6 g kg^{-1} yr^{-1}). Angers (1992) reports that the highest accretion of SOM under alfalfa stands occurred in the course of the third year.

Carbon inputs from alfalfa root systems to soil were assessed to be five times higher than corn root contributions (Angers, 1992). Plant tissue decomposition rates are lower for roots than for shoots. Broadbent and

Nakashima (1974) reported that after 60 days of barley (*Hordeum vulgare* L.) tissue incubation in soils, 30% of the roots and 55% of the shoot had decomposed.

Incorporation of fresh plant residues interferes with SOM decomposition rates, or basal mineralization. Broadbent and Nakashima (1974) reported increased rates of SOM mineralization, called ‘priming effect’, when plant residues were incorporated to soil. On the other hand, Watkins and Barraclough (1996) argue that the soil microbial activity can be diverted from SOM to plant tissue mineralization, therefore decreasing SOM mineralization rates. Soil incorporation of alfalfa shoots results in a direct increase in net mineralization due to the low C/N of alfalfa tissues (Li and Mahler, 1995; Smith and Sharpley, 1990). On the contrary, corn residue incorporation to soils resulted in a net immobilization of soil mineral nitrogen (Smith and Sharpley, 1990). Staver and Brinsfield (1990) reported lower rates of SOM mineralization in corn fields vs. bare fallow soils, during the corn growing season.

Alfalfa Rotation Effect on Corn

The enhancement of corn yield by either rotation or intercropping with legumes, has been reported by several authors (Clément et al., 1992; Lyon and Bizzel, 1993; Paré et al., 1993a & 1993b; Ta and Faris, 1987; Torbert et al., 1996; Zhang and Blevins, 1996). This "rotation effect" has been linked to increased soil nitrogen and improved soil aggregation. Green and Blackmer (1996), working with corn - soybean (*Glycine max* L.) rotation, considered that N immobilization by corn residues explains the legume rotation effect. Legume residues did not immobilize SOM-mineralized nitrogen, as did corn residues. Köpke (1995) suggested that the low rooting density of most legumes results in higher amounts of SOM-mineralized nitrogen available for the succeeding crop.

Numerous studies (Hesterman et al. 1986a & 1986b, Barnes et al. 1978 & 1983, Groya and Sheaffer 1985) have reported the yield increasing effect of alfalfa on the subsequent non-legume crop. Nitrogen replacement values of alfalfa to a succeeding corn crop were estimated from 90 to 125 kg N ha-1 (Bruulsema and Christie, 1987). Fox and Piekielek (1988) report a total N replacement value for a three-year-old alfalfa stand followed by three years of consecutive corn to be of 167 kg N ha^{-1}. Hesterman et al. (1986a) reported that alfalfa crowns and roots contained from 85 to 106 kg N ha^{-1} in the fall of the seeding year. Plowed down alfalfa shoots and roots contributed up to 160 kg N ha^{-1} (Hesterman et al. 1986a). Specific alfalfa varieties were selected for their high content of reduced nitrogen in the crowns and roots (Barnes et al., 1978; Barnes et al., 1983).

The alfalfa nitrogen replacement value for succeeding corn crops is still underestimated or neglected by many farmers, resulting in wasted fertilizers and groundwater pollution problems (El-Hout and Blackmer, 1990; Peterson and Russelle, 1991).

Corn and Alfalfa Modifications of Soil Physical Properties

Plant root systems and crop residue management modify soil physical properties, affecting retention and movement of water in soils (Prasad and Power, 1991;). Part of the rotation effect of legume crops has been attributed to improved soil physical properties (Folorunso et al., 1992, McVay et al., 1989). Improved soil structural stability under alfalfa stands have been reported by several authors (Angers, 1992; Perfect et al., 1990). Both alfalfa and maize root systems have been reported to increase the saturated hydraulic conductivity of soils free of previous root channels (Li and Ghodrati, 1994). Meek et al. (1992) observed a six-fold increase in the hydraulic conductivity of compacted sandy loam when planted with alfalfa. Mitchell et al. (1995) reported that, contrary to wheat, alfalfa root systems have the ability to increase the saturated hydraulic conductivity of swelling soils.

Nitrate Leaching Under Alfalfa and Corn Crops

Alfalfa has been considered beneficial as well as detrimental to the reduction of nitrate leaching losses. Lamb at al. (1995b) reported that alfalfa has a great ability for absorbing nitrates during critical periods of nitrate pollution. The deep root system of alfalfa can recycle nitrates leached to depth inaccessible to other crops (Blumenthal and Russelle, 1996). On the other hand, mineralization bursts can lead to high levels of nitrate leached to the ground water, if not timely matched by crop consumption (Cambell et al., 1994; Philipps and Stopes, 1995). Nitrate leaching occurs at low levels under a living alfalfa stand (Peterson and

Russelle, 1991). Irrigation of alfalfa fields slightly increase NO_3-N leaching (Peterson and Russelle, 1991). Robbins and Carter (1980) reported up to 44 kg $N0_3$-N ha^{-1} leached below the root zone of irrigated alfalfa. Owens (1990) reported that alfalfa planted to fertilized corn decreased leachate concentrations from a high of 40 mg NO_3-N l^{-1} to as low as 5 mg NO_3-N l^{-1}. Non-nodulating alfalfa varieties have been developed for the purpose of removing nitrates from the soil profile (Lamb et al, 1995a; Lamb et al, 1995b).

Nitrate leaching in soils under corn production depends on tillage systems and nitrogen fertilizer inputs. Corn nitrogen fertilization tends to generate N leaching problems when applications are in excess of plant uptake (Angle et al., 1993; Gast et al., 1978). Gast et al. (1978) reported little nitrate leaching differences between corn fields receiving from 20 to 112 kg N ha^{-1}. In a three-year study using ^{15}N-depleted ammonium nitrate applied at 168 kg N ha^{-1}, Kitur et al. (1984) retrieved about 35% of applied N in plant biomass, 40% in soils and 25% lost by leaching and denitrification. No-tilled (NT) soils present higher infiltration rates (Bissett and O'Leary, 1996; Dao, 1993), higher saturated hydraulic conductivities (Bissett and O'Leary, 1996; Comia et al., 1994), higher volumetric soil water content (Dao, 1993), and higher drainage water flows (Randall and Iragavarapu, 1995; Weed and Kanwar, 1996) than conventional tillage (CT) soils. This difference is explained by the continuity of soil macropore networks, especially root-induced macropores (RIMS), in NT soils (Comia et al., 1994; Lal and Vandoren, 1990; Reynolds et al., 1995; Smucker et al., 1995; Waddell and Weil, 1996). Reynolds et al. (1995) observed that NT soils are specially enriched in 0.1 to 0.3 mm macropores. Zhai et al. (1990) suggested that higher soil water contents in NT vs. CT corn production systems result from reduced evaporation under NT treatment due to the mulch effect. Soil water leachates present higher nitrate concentrations in CT vs. NT corn production systems (Randall and Ivaragarapu, 1995; Weed and Kanwar, 1996). Combining drainage flow and nitrate concentration, most researchers observed slightly higher nitrate leaching losses out of CT than NT soils under corn production (Randall and Ivaragarapu, 1995; Weed and Kanwar, 1996), while some reported the opposite (Huang, 1995)

Conclusions

Alfalfa rotation effect on succeeding corn crops has been widely reported. Nevertheless, not all alfalfa-fixed nitrogen is absorbed by the following corn crop, resulting in increased nitrate leaching under poor management practices. The proportion of nitrogen available to the next corn crop depends on a series of little-studied factors. The root to shoot ratio of plowed down alfalfa depends on the age of the stand, i.e. from a few months to several years, and the elapsed time between plowdown and the last harvest. Establishing best management practices for corn following alfalfa plowdown requires a determination of the specific contributions of above and below ground alfalfa plant parts to soil N pools. Hence, alfalfa roots and shoots potentially differ in their nitrogen contents, decomposition rates, denitrification rates, and specific migration of mineralization products through the soil. Alfalfa root systems can modify soil physical properties such as the saturated hydraulic conductivity, further influencing nitrate leaching rates. The timely development of corn root systems following alfalfa plowdown is critical for catching nitrates before being leached below root-zone soil. The spatial distribution of the corn root system is another potential factor influencing the availability of alfalfa-generated nitrogen to corn. Direct recolonization of alfalfa root channels by corn roots potentially enhances N absorption while reducing water flow.

Chapter one investigates the specific contributions of alfalfa above and below ground plant parts to soil organic and mineral nitrogen pools, as well as leaching and denitrification losses. Chapter two analyzes the effects of alfalfa root systems and shoot mulch on soil physical properties. Chapter three focusses on the nitrogen contributions of alfalfa stands to succeeding corn crops, and on nitrate leaching in a corn alfalfa corn succession. Chapter four investigates root distribution and recolonization in a corn alfalfa corn succession.

CHAPTER 1

Modifications of soil nitrogen pools and fluxes in response to alfalfa root systems and shoot mulch.

ABSTRACT

Dynamics of soil and plant nitrogen pools were studied in a Kalamazoo loam soil (mixed, mesic Typic Hapludalf) over a two-year period under: bare fallow soil (B), bare fallow soil with alfalfa shoot mulch applied after each harvest (BS), alfalfa with shoots removed after each harvest (A), alfalfa with alfalfa shoot mulch applied after each harvest (AS). Organic nitrogen pools were monitored in alfalfa herbage yield, shoot mulch, alfalfa crowns and roots, soil incorporated debris, and total soil nitrogen contents per horizon to depths of 150 cm. Mineral nitrogen fluxes were monitored by suction lysimeters, soil extraction and evaluation of soil denitrification rates. Alfalfa herbage yields were increased over 40% by shoot mulch application for the second growing season. Total root and crown biomass and nitrogen contents were not affected by treatments. Living alfalfa stands kept soil mineral nitrogen at very low levels, whether shoot mulch was applied or not. Soluble mineral nitrogen concentrations decreased earlier in the Fall in the upper horizons of bare fallow soils receiving alfalfa shoot mulch,

suggesting enhanced leaching from bare soil under alfalfa mulch. Living alfalfa stands increased soil organic matter levels compared to bare fallows, though significant augmentations could only be shown in the Bt_1 horizon. Alfalfa shoot application more than doubled denitrification rates of soils under bare fallow and alfalfa stands. Mineralization of the SOM under bare fallow produced mineral nitrogen in excess of 150 kg N ha^{-1} from May to October of the second growing season, corresponding to a SOM mineralization rate of 2.6%.

INTRODUCTION

The fate of soil mineral nitrogen generated by decaying plant tissues and mineralized soil organic matter (SOM) is of crucial interest to sustainable agriculture. Reduced-input farming requires the optimal usage of green manure and plant residue nitrogen by the following cash crop (Eltun, 1995). Plant residues and SOM-derived nitrogen have to be contained in the top of the soil profile in order to: (1) maximize N availability to crops, (2) minimize NO_3 leaching losses to groundwater, (3) minimize N_2O gaseous losses involved in the greenhouse effect (Peterson and Russelle, 1991).

Alfalfa dinitrogen fixation contributes more than 1 billion kg N y^{-1} to N inputs in the American corn belt (Peterson and Russelle, 1991). Net production of soil nitrogen (i.e., soil N gain + plant uptake) by alfalfa has been reported to be greater than red clover and much greater than peas or vetch (Lyon and Bizzell, 1993). The improvement of the soil nitrogen status has mainly been attributed to

the high dinitrogen fixation potential of alfalfa (Fox and Piekielek, 1988).

Alfalfa has been considered beneficial as well as detrimental to the reduction of nitrate leaching losses. Lamb et al. (1995) reported the great potential for alfalfa to absorb nitrates especially during the spring and autumn when nitrate leaching is the greatest. The deep root system of alfalfa can recycle nitrates leached to depths inaccessible to other crops (Blumenthal and Russelle, 1996). On the other hand, mineralization bursts can lead to high levels of nitrate leached to the ground water if not matched by crop consumption (Cambell et al., 1994; Philipps and Stopes, 1995).

Establishing best management practices for cash crops following alfalfa plowdown requires the determination of the specific contributions by above and below ground alfalfa plant parts to soil N pools. Alfalfa roots and shoots potentially differ in their nitrogen contents, decomposition rates, denitrification rates, and specific migration of mineralization products through the soil. Efficient storage of below ground nitrogen under alfalfa stands is influenced by the distribution over time of the different N pools (root-N, SOM-N, mineral N) within the different soil horizons. Incorporation of fresh plant residues interferes with SOM decomposition rates, or basal mineralization. Broadbent and Nakashima (1974) reported increased rates of SOM mineralization, called 'priming effect', when plant residues were incorporated to soil. On the other hand, Watkins and Barraclough (1996) argue that the soil microbial activity can be diverted from SOM to plant tissue mineralization, therefore decreasing SOM mineralization rates. Soil incorporation of alfalfa shoots results in a direct

increase in net mineralization due to the low C/N of alfalfa tissues (Li and Mahler, 1995; Smith and Sharpley, 1990). Application of mineral or easily mineralizable nitrogen increases alfalfa yields (Mathers et al., 1975; Schmitt et al., 1994). Most studies report that increased levels of soil mineral nitrogen diminish symbiotic fixation (Cherney and Duxbury, 1994; Phillips and DeJong, 1984). Others report that alfalfa presents the remarkable ability to continue symbiotic fixation at high soil mineral nitrogen levels (Lory et al., 1992; Lamb et al., 1995).

The objective of our study was three-fold: (1) to identify and quantify the storage pools for the nitrogen released from decaying alfalfa shoot tissues in soils under living alfalfa stands, (2) to quantify and compare pathways of nitrogen losses in alfalfa systems in comparison to bare soil fallows, and (3) to identify periods of maximum soluble mineral nitrogen release attributable to soil organic matter, alfalfa shoot mulch and alfalfa root systems.

MATERIAL AND METHODS

Experimental Design and Treatments

A field experiment was conducted at the NSF-supported Long-Term Ecological Research (LTER) site at the Kellogg Biological Station in southwestern Michigan. Four treatments were considered: bare soil (B), bare soil to which alfalfa shoots were applied after harvest (BS), alfalfa with shoots removed after harvest (A), alfalfa with shoots applied on the soil surface after harvest (AS). Each treatment was replicated four times in a randomized

complete block design. Microplots, 6 by 10 m each, were installed in a Kalamazoo loam soil (fine-loamy, mixed, mesic Typic Hapludalf) in late August 1994. The preceding crop was corn, fertilized at 123 kg N ha^{-1}. Moldboard plowing was performed to depth of 23 cm following corn harvest. All plots were tilled and trafficked equally. Alfalfa was drilled in half of the plots on 30 August 1994. The bare soil plots were also drilled without seeds. The bare soil plots were kept free of weeds by applications of glyphosate at approximately 6 weeks intervals between April and August of each year. Plots received no nitrogen fertilizer. Potash was applied at rate of 280 kg/ha of K_2O equivalents, together with 2.2 kg/ha of boron, on 13 June 1996. Lime was applied at rate of 2.5 t/ha on 14 June 1996.

The alfalfa plots were harvested 3 times in each of the 1995 and 1996 growing seasons. At harvest, alfalfa plants were cut 5 cm above the soil by a 90 cm wide sickle-bar power mower. After cutting, the alfalfa shoots were raked from the A and AS plots, and redistributed equally across both the AS and BS plots. Alfalfa shoots were applied by volume. Application rates were assessed from 0.076 m^3 subsamples of known weight and moisture contents and similarly compacted to the rest of the applied plant material. At the first harvest, the alfalfa was applied as uniformly as possible across all plots. The layer of alfalfa mulch proved to physically impede alfalfa regrowth. Consequently, subsequent applications were conducted by uniform manual application of the alfalfa shoots between the rows. Accumulated applications of alfalfa shoots to both BS and AS treatments approximated 232 and 585 kg N ha^{-1} by the end of the first and

second growing season, respectively. A one meter ineffective border was considered around each plot. The remaining surface within each plot was allocated to: 1) non destructive sampling with *in situ* instruments (2 x 4 m), 2) yield assessment (4 x 4 m), and 3) destructive sampling (2 x 4 m). Plots were separated by a surface plastic barrier, protruding 5 cm from the ground to prevent run-off/run-on between plots.

Measurements

Alfalfa yields at each harvest were estimated by sampling on a non-disturbed 4 by 4 m area reserved for this purpose. Subsamples for moisture content were taken immediately, weighed, dried at 70°C, and reweighed. Subsamples were finely ground (< 0.5 mm) for total carbon and nitrogen analyses by dry combustion method (Kirsten, 1983) using a carbon / nitrogen / sulfur analyzer NA1500 series 2 (Carlo Erba Stumentazione, Milano, Italy).

Each field plot was equipped with 1 bar high-flow suction lysimeters model 1900 (Soil Moisture, Santa Barbara, California) for soil solution extraction. Suction lysimeters were installed at depths of 15, 35 and 60 cm, to intercept the Ap and Bt_1 and Bt_2 horizons, as determined by preliminary soil sampling along the central regions of the plots. Depth of the Bt_2/C interface averaged 70 cm. Calumel-cap suction lysimeters were installed at a 45° angle into the soil, after planting alfalfa. Volumetric soil water contents were assessed using time domain reflectometry (TDR) technology. TDR probes were inserted horizontally at 15, 35 and 60 cm in a small profile dug in every plot before planting, and shielded cables were brought to the soil surface. Instrument installation profiles were described and used for horizon delineation. The profiles were recompacted horizon by horizon and the cable buried before planting. TDR probes were assembled at the Soil Biophysics Laboratory (Michigan State University, MI, U.S.A). Effective length of the probe into the soil profile was of 28.5 cm. TDR meter readings were collected from the cables at the soil surface using a Tektronix cable tester model 1502C (Tektronix Inc, Beaverton, Oregon, U.S.A.). The Topp's equation was used for TDR curve analysis (Topp et al., 1980). Soil solution samples were analyzed for NO_3 and NH_4 by the cadmium reduction method using a QuickChem Automated Ion Analyzer (Lachat Instruments, Milwaukee, WI).

Disturbed soil samples were extracted on 14 May and 12 October 1996 with Giddings hydraulic probe (Giddings Co., Ft. Collins, CO) equipped with a 8.9 cm diameter probe. Spring samples were taken to depths of 150 cm. Fall samplings were generally limited to the middle regions of the Bt_2 horizon, as the hydraulic probe could not be inserted trough the deeper dry clay layers of the Bt_2 horizon. Two cores were extracted from each plot and divided longitudinally into two equal halves. Each half-core was then divided into Ap, Bt_1, Bt_2, C_1 and C_2 horizons. One half was used for mineral nitrogen, total carbon and total nitrogen analyses and roots were washed from the other half. Gravimetric soil water contents were determined on subsamples of soils dried in a forced-air oven at 105 °C for 24 hours. Field-moist 20g subsamples were extracted for NO_3 and

NH_4 with 1 N KCl. The remaining part of the soil samples was air dried and finely ground (< 0.5 mm) for total carbon and nitrogen analyses by the dry combustion method using a carbon / nitrogen / sulfur analyzer NA1500 series 2 (Carlo Erba Stumentazione, Milano, Italy).

Alfalfa roots were extracted from the soil matrix by hydropneumatic elutriation (Smucker et al., 1982) and stored at 4°C in 20% (v/v) methanol solution. The diamater of the Giddings probe, i.e. 8.9 cm, was considered insufficient for proper root estimations in the first 15 cm of the soil as samples had to be taken in or out of the row, including or rejecting alfalfa tap roots and, therefore, could not accurately represent the surface ratio of row to interrow. Consequently, two 200 cm^2 samples per plot were taken in October 1996 to depth of 15 cm, centered on a alfalfa row and extending into one half of an interrow on each side. Alfalfa plants were clipped at the crowns and the soil surface was cleared of debris. Samples were washed by hydropneumatic elutriation, then divided into roots and soil-incorporated organic debris. Each fraction was analyzed separately for total C and N by the dry combustion method.

The Ap horizon was sampled in May and November 1995 and in October 1996 to depth of nine inches to monitor the evolution of total C, N and C/N ratio. Ten subsamples per plot were collected, mixed into one composite sample, air dried and finely ground (< 0.5 mm).

Alfalfa shoot mulch biomass remaining on the soil surfaces of the BS and AS plots after two years of experiment were sampled in December 1996. A 30 cm diameter PVC ring was randomly positioned on the plots, and all mulch material carefully hand-picked inside the ring. The two samples per plot were combined, oven dried at 70°C, finely ground (< 0.5 mm), and analyzed for total carbon and nitrogen by the oxygen-enriched dry combustion method, using a carbon / nitrogen / sulfur analyzer, model NA 1500, series 2 (Carlo Erba Stumentazione, Milano, Italy).

Soil denitrification rates were estimated in June 1996 by acetylene inhibition in static cores (Tiedje et al., 1989). Five 15 cm long cores were collected per plot in the three first replicated blocks. Cores were immediately caped with rubber stoppers, kept in the shade in the field and injected directly after collection of the entire batch of samples. Acetylene was produced by the reaction of carbide minerals with water.

Statistical Analyses

Data sets with a maximum of six sampling dates were analyzed separately by date using the general linear model procedure of the SAS system (SAS Institute, 1989). Data were analyzed considering four individual treatments, with means and Fisher's least significant differences ($LSD_{0.05}$) reported. Denitrification data, often reported as log-normal distributed (Tiedje et al., 1989), were tested for normality but were judged at most modest with respect to robustness of inference and not improved upon by logarithmic transformation. Consequently, analyses proceeded on the original scale of measurement . Mean separation tests conducted on original and log-transformed data produced inconsequential differences in mean discrimination.

Suction lysimeter data, including more than 20 measurement dates, were analyzed using univariate repeated measures techniques with a spatio-temporal correlation structure based on the mixed procedure of the SAS system (Gregoire et al., 1995; Schabenberger and Gregoire, 1995; Littell et al., 1996). This analysis permits inference on main effects, simple effects and interactions between treatments and treatments by time while simultaneously accounting for the fact that repeated observations on the same experimental unit are not independent. Since measurements were collected at three depths at every given point in time, correlations over time at a given depth, across depths at a given time, and across time and depths needed to be incorporated. The unequal spacing of measurements in time along with the pattern of missing observations for certain depths required a continuous spatio-temporal correlation process. Thorough investigation of various candidate correlation models resulted in the choice of an exponential correlation model where continuous distance between location is measured as euclidian distance in time and depth. The treatment structure was entered as a 2x2 factorial with factors plant (P; levels alfalfa/bare soil) and mulch (M; levels applied/not applied) to gain further insight in the interaction structure. Analyses were conducted separately for 1995 and 1996. Soluble mineral N contents were statistically modeled for each treatment, in 1995 and 1996 (Figures 1.3 and 1.4), using polynomial functions whose order corresponded to the significant multiple time interactions with treatments.

RESULTS AND DISCUSSION

Herbage Biomass and Nitrogen Contents

Application of harvested shoots between the alfalfa rows progressively increased alfalfa yields, with yields on the alfalfa plus shoots (AS) becoming significantly greater than yields on the alfalfa without harvested shoots (A) at the first harvest of year 2 (Table 1.1). These findings are consistent with other studies reporting that application of mineral or easily mineralizable nitrogen increases alfalfa yields (Mathers et al., 1975; Schmitt et al., 1994). Nitrogen concentrations and C/N ratios of the shoots were not significantly altered by shoot application at harvest (Table 1.1). Groya and Sheaffer (1985) also reported that alfalfa shoot application did not significantly alter total alfalfa N yields in the seedling year. However, total nitrogen contents per harvest mimicked biomass yields, where 169 kg N ha^{-1} were harvested from the AS treatment for the first harvest of the second growing season. The amount of nitrogen from alfalfa shoot mulch which was directly recycled into the growing alfalfa plant is difficult to assess, as the rate of dinitrogen fixation can be influenced by soil nitrate levels (Heichel et al., 1984; Cherney and Duxbury, 1994). During the second growing season, plant N contents totaled 100 kg N ha^{-1} more in the AS than in the A treatments, indicating that alfalfa plants absorbed at least this amount from the mineralization of surface applied alfalfa shoots. Alfalfa plant N in the AS treatment increased 152 kg N ha^{-1} from the first to the second year, while plant N increased only 25 kg N ha^{-1} for the A treatment.

Table 1.1. Yields, nitrogen contents and C/N ratios of alfalfa cuttings, with shoots applied at harvest (A) or with no shoots applied (AS).

Harvest Date	Yields		Total Nitrogen				C/N ratio	
	A	AS	A	AS	A	AS	A	AS
	— kg ha^{-1} —		—— % ——		— kg ha^{-1} —			
9 June 95	1393	1045	3.57	3.52	50	37	12.0	12.2
24 July 95	2960	2517	3.23	3.02	95	77	13.0	14.2
31 Aug 95	1439	1567	4.10	3.98	59	63	10.7	11.0
31 May 96	3102	4163*	3.78	4.07	118	169*	11.4	10.6
3 July 96	1782	1946	3.45	3.59	62	70	12.4	12.0
21 Aug. 96	1512	2792	3.22	3.29	49	90	13.6	13.3

* Within dates, significant at $P \leq 0.05$.

Root, Crown, Soil Incorporated Debris and Mulch N Contents

Root dry biomass yields of alfalfa were not significantly altered by shoot application, in the top 15 cm of the soil profile in October 1996 (Table 1.2), and in the Bt horizons in May and October 1996 (Figure 1.1). Total root biomass contained in the Ap, Bt_1 and Bt_2 horizons in October 1996 was of 3863 and 4417 kg ha^{-1} for A and AS respectively. Reported alfalfa root biomass vary greatly among studies. Groya and Shaeffer (1985) reported dry matter root biomass of 2.5 Mg ha^{-1}, with samples collected to depth of 15-20 cm and root extraction conducted without hydropneumatic elutriation. Lory et al. (1992) found 3.22 Mg and 0.83 Mg of alfalfa root biomass per hectare to depths of 0-35 cm and 35-70 cm respectively. Blumenthal and Russelle (1996) reported up to 7850 kg ha^{-1} of dry biomass alfalfa roots in the top 35 cm of the soil profile and 1122 kg ha^{-1} from

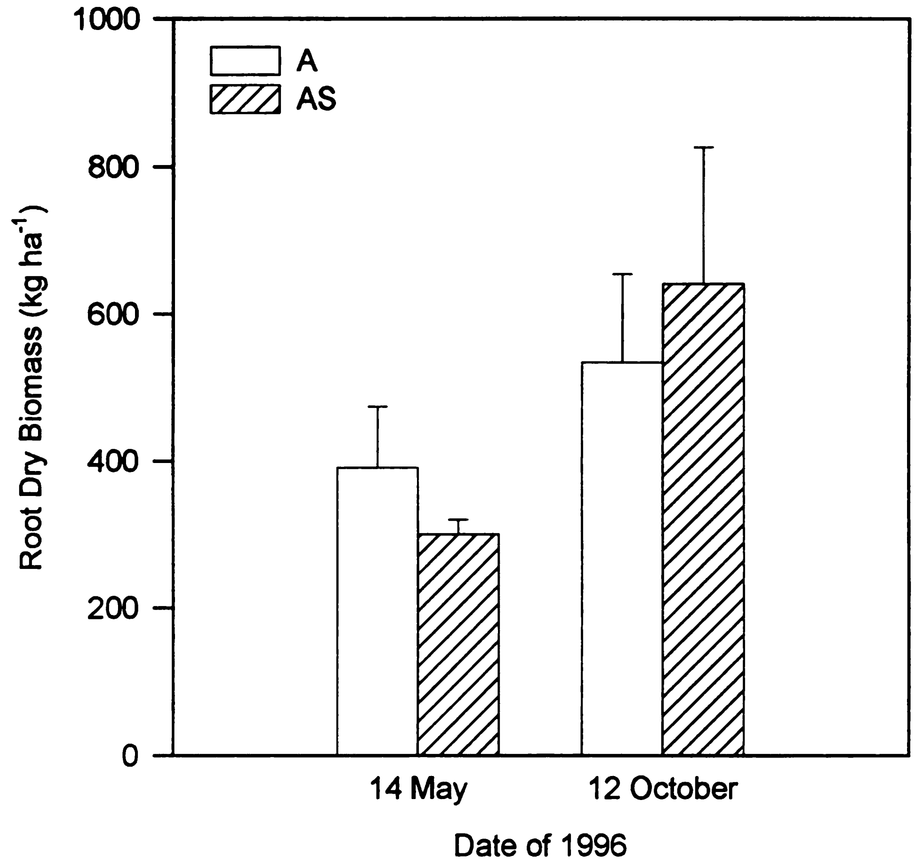

Figure 1.1. Dry biomass of alfalfa roots in the Bt horizons of soils under alfalfa stands with no alfalfa shoot mulch applied (A) and with alfalfa shoot mulch applied (AS), in May and October 1996.
Standard errors for n=4.

37 to 70 cm. Alfalfa root contents in the Bt horizons increased 37% and 114% for A and AS treatments respectively, from 14 May to 12 October 1996 (Figure 1.1). Nitrogen contents of the roots were not significantly modified by alfalfa shoot mulch application (Table 1.2).

Table 1.2. Biomass and carbon-nitrogen composition of alfalfa crowns, roots and soil incorporated organic debris for plots under alfalfa (A), and alfalfa with alfalfa shoot mulch (AS), sampled to depth of 15 cm on 12 October 1996.

Biomass Pool	Treatment	Biomass	Carbon	Nitrogen	Nitrogen	C/N ratio
		kg ha^{-1}	——— %	———	kg ha^{-1}	
Crowns	A	889	31.4	2.33	20.7	13.6
	AS	1274	36.3	2.53	32.2	14.4
Roots	A	3329	30.1	1.97	65.6	15.3
	AS	3776	32.6	2.30	86.8	14.3
Soil Debris	A	1070	27.2	1.76	18.8	15.5
	AS	1115	32.6*	2.26**	25.1	14.4

*,** Within biomass pools, significant at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Alfalfa crowns dry biomass, nitrogen contents and C/N ratios were not significantly modified by alfalfa shoot mulch (Table 1.2). Total amounts of nitrogen present in alfalfa crowns and roots in October 1996 averaged 97 and 133 kg N ha^{-1} for A and AS respectively. These results are consistent with values reported by Hesterman et al. (1986) ranging from 85 to 106 kg N ha^{-1} in alfalfa crowns and roots in the fall of the seeding year.

Soil incorporated debris presented highly significant ($P < 0.01$) increases in nitrogen concentration with shoots applied to soil surface (Table 1.2).

However, total amounts of soil incorporated debris were not significantly modified by treatment. This suggests that little surface-applied alfalfa mulch was incorporated into the Ap horizon during the two years of treatment. Similar amounts of soil incorporated debris in both treatments could also result from higher input and incorporation rate under mulch, together with higher decomposition rate due to increased nitrogen availability under alfalfa mulch.

Decomposition and mineralization of alfalfa shoot mulches were greatly enhanced by the presence of a living alfalfa stand (Figure 1.2). Total dry matter biomass of alfalfa mulch remaining on the soil surface in December 1996 showed a highly significant ($P < 0.01$) treatment effect, and averaged 3747 kg ha^{-1} for AS and 10067 kg ha^{-1} for BS treatments (Figure 1.2). Nitrogen concentration and C/N ratio of remaining mulch were not significantly altered by treatment and averaged 2.24%, and 17.9 respectively (data not reported). Total nitrogen contents in remaining mulch were of 84 and 225 kg N ha^{-1}, in AS and BS respectively. The alfalfa shoot mulch contained from 14% (AS) to 38% (BS) of the total shoot N applied over the two year period.

Soluble Soil Mineral Nitrogen

Mineral nitrogen concentrations, i.e. the sum of NO_3-N and NH_4-N concentrations, of suction lysimeter extractions were combined with TDR volumetric soil water contents for each horizon depth to report soluble mineral N contents in kg ha^{-1}. These results are expressed in the same units as 1 N KCl

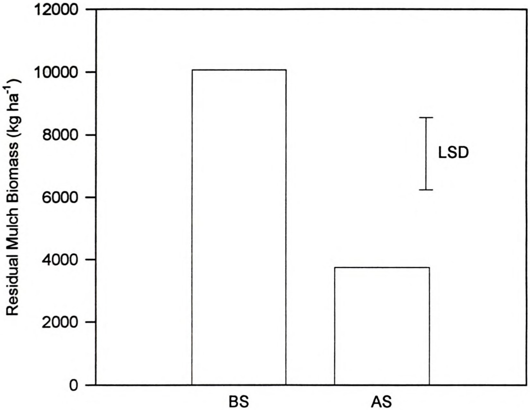

Figure 1.2. Residual biomass of accumulated alfalfa mulch applied to soils under bare fallow (BS) and alfalfa stands (AS), after two years of treatment. Fishers' least significant difference ($LSD_{0.05}$) reported.

soil extractions.

Few changes in soluble mineral nitrogen were observed on the alfalfa treated plots in 1995 and 1996, whether shoots were applied or not, while the bare soil exhibited considerable dynamics (Figures 1.3 and 1.4). Alfalfa stands kept mineral nitrogen contents in the soil solution at very low levels throughout the year. Soluble soil nitrogen contents became significantly lower under alfalfa stands than under bare fallow soils at any depths, whether shoot mulch was applied or not (Table 1.3). Alfalfa roots absorbed nearly all nitrates from the soil solution at any sampling depth, whether shoot mulch was applied or not, resulting in no significant mulch effect on alfalfa plots (Table 1.4). These results confirm the high prevention potential of alfalfa for nitrate leaching, as previously reported by several authors (Lamb et al., 1995; Blumenthal and Russelle, 1996).

Peaks of maximum soluble nitrogen were reached under BS treatment in early October, November and December 1995 in the Ap, Bt_1 and Bt_2 horizons, respectively. Similar dynamics were observed under B treatment, however peaks of soluble mineral N were delayed compared to BS treatment (Figure 1.3). These findings suggest that substantial mineral N leaching occurred under bare fallow (B and BS) and that alfalfa shoot mulch application promoted leaching earlier in the fall. Hence, soluble mineral N contained in the Ap horizon of bare fallow soils was significantly lowered by alfalfa shoot mulch application, in spring 1996 (Figure 1.4, Table 1.4). In Fall 1996, soluble mineral N contents peaked in bare fallow soils earlier in upper than in deeper horizons, which confirms the leaching dynamics observed in 1995. However, opposite to 1995, no temporal difference

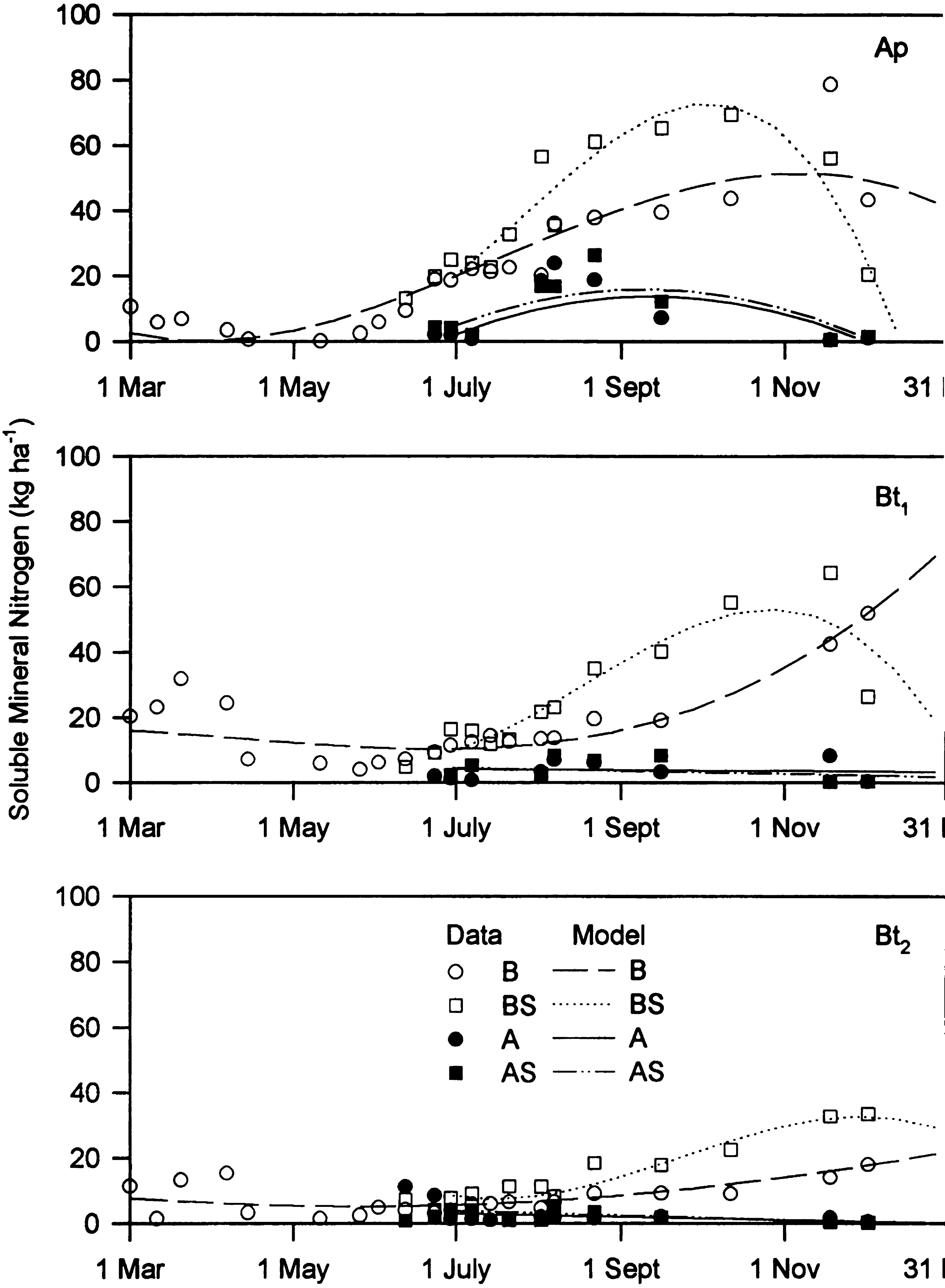

Figure 1.3. Soluble mineral nitrogen contained in the top three horizons of soil under bare fallow (B), bare fallow with alfalfa shoot mulch (BS), alfalfa (A), and alfalfa with alfalfa shoot mulch (AS), in 1995.

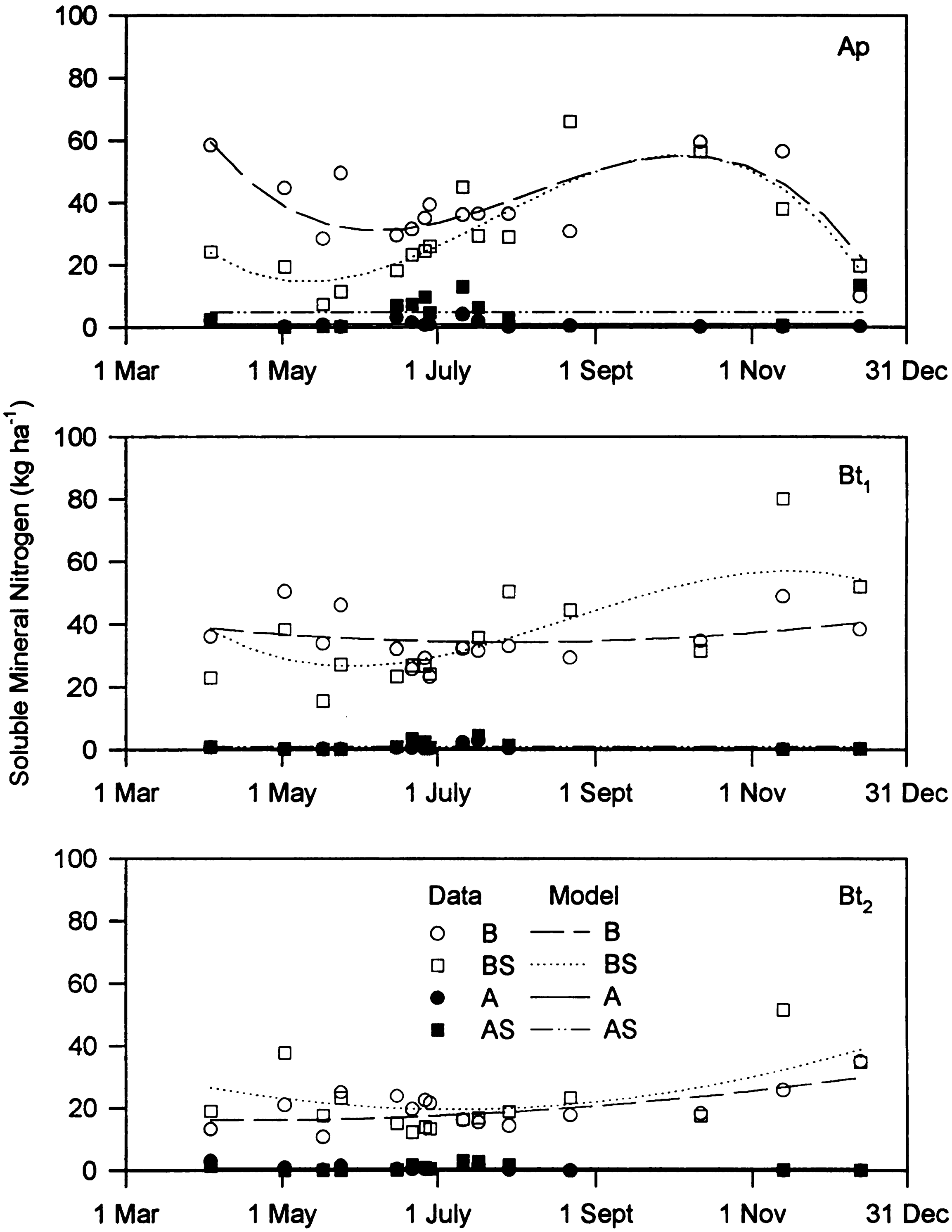

Figure 1.4. Soluble mineral nitrogen contained in the top three horizons of soils under bare fallow (B), bare fallow with alfalfa shoot mulch (BS), alfalfa (A), and alfalfa with alfalfa shoot mulch (AS), in 1996.

Table 1.3. Simple effects tests for the factor 'plant', i.e. presence or absence of living alfalfa crop, from repeated measures analysis of soluble mineral nitrogen contents for 1995 and 1996.

Comparison	Depth	Significance of 'Plant' effect	
		1995	1996
B vs. A	15 cm	***	***
BS vs. AS	15 cm	NS†	***
B vs. A	35 cm	**	***
BS vs. AS	35 cm	NS	***
B vs. A	60 cm	NS	**
BS vs. AS	60 cm	NS	***

, * Significant at $P \leq 0.01$, and $P \leq 0.001$, respectively.
† Non-significant at $P \leq 0.05$.

Table 1.4. Simple effects tests for the factor 'mulch', i.e. application or no application of alfalfa shoot mulch, from repeated measures analysis of soluble mineral nitrogen contents for 1995 and 1996.

Comparison	Depth	Significance of 'Mulch' effect	
		1995	1996
B vs. BS	15 cm	***	*
A vs. AS	15 cm	NS†	NS
B vs. BS	35 cm	NS	NS
A vs. AS	35 cm	NS	NS
B vs. BS	60 cm	NS	NS
A vs. AS	60 cm	NS	NS

*, *** Significant at $P \leq 0.05$, and $P \leq 0.001$, respectively.
† Non-significant at $P \leq 0.05$.

in leaching pattern was observed between B and BS plots. This probably was due to the excessively dry growing season (Rasse et al., 1997).

The time sequence of soluble mineral N contents in the different horizons was used to estimate N losses, particularly for B and BS treatments, which undergo large variations of soil nitrate concentrations. It was assumed that there was no significant upward movement of soil nitrates in these profiles. Differences in soluble mineral N contents for each horizon between two dates represent the minimum production and losses of soil N. Each plot was uniquely characterized by the depths of its horizons, and soluble mineral N gains and losses were summed up over the top 70 cm of the soil profile. Soluble mineral N gain in an horizon was only accounted for if it could not be explained by a leaching loss from an upper horizon. Soluble mineral N loss from an horizon was only accounted if it could not be retrieved from an adjacent lower horizon. Minimum soluble mineral N productions and losses over the top 70 cm of the soil profile between June 26, 1995 and December 13, 1996 were of 254.6 and -201.9 kg N ha^{-1} for the B treatment, and of 365.3 and -291.6 kg N ha^{-1} for the BS treatment.

Extractable Soil Mineral Nitrogen

Soil mineral N contents, as extracted by 1 N KCl, were always higher than soluble mineral N from suction lysimeters. The correlation between soluble and extractable mineral N in A and AS plots was poor at very low soluble N contents. When substantial amounts of mineral N were present in the soil solution, i.e. in the B and BS plots, soluble and extractable mineral contents followed an exponential relationship (Figure 1.5). In Spring 1996, extractable mineral N contents in B and BS soils were five times higher than in A and AS soils (Table 1.5). Highest mineral N contents were found in the Bt_1 and C_1 horizons of B and BS plots respectively. These findings confirm suction lysimeter data showing higher nitrate leaching from fall to spring when shoots were applied to bare soils. Extractable mineral N contents were increased in B and BS treatments from May to October 1996, while A and AS showed little differences (Table 1.5). The Ap horizons of the BS plots accumulated an average of 163 kg NO_3-N + NH_4-N ha^{-1}, increasing from 15.2 to 178.5 kg N ha^{-1}. Total mineral N accumulations over summer and fall 1996 in the Ap and Bt horizons were of 204.8 kg N ha^{-1} in BS plots and of 87.2 kg N ha^{-1} in B plots. During the same period of time, suction lysimeter data indicate that minimum soluble mineral N losses out of the Ap and Bt horizons were of 66.7 kg N ha^{-1} for B and 59.8 kg N ha^{-1} for BS. Consequently, total mineral N produced from May to November 1996 is of 153.9 and 264.6 kg N ha^{-1} for B and BS respectively.

Total Soil Carbon and Nitrogen

Total carbon and nitrogen levels in the Ap horizon were analyzed in spring and fall of 1995 and 1996 (data not reported). No significant differences between treatments were observed for any date. Data analyses were complicated by a very strong gradient of soil organic matter contents along the 96 meters transect

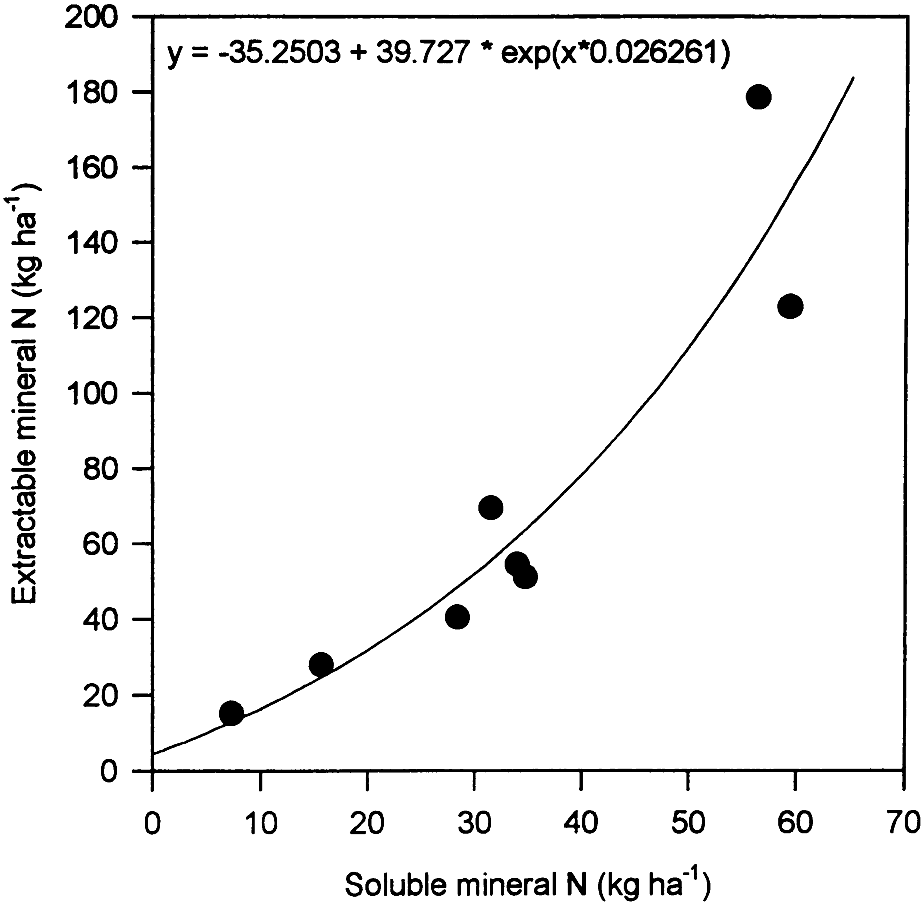

Figure 1.5. Comparison of soluble and extractable mineral nitrogen contents (NO_3 + NH_4) in bare fallow soils in 1996.

Table 1.5. Extractable mineral nitrogen contents per horizons in a Kalamazoo loam soil under bare fallow (B), bare fallow with alfalfa shoots applied (BS), alfalfa (A) and alfalfa with alfalfa shoot applied (AS).

	14 May 1996				12 October 1996			
Horizon	B	BS	A	AS	B	BS	A	AS
	kg NO_3-N + NH_4-N ha^{-1}							
Ap	40.4[a†]	15.2[b]	6.7[bc]	7.4[c]	123.0[a]	178.5[a]	7.2[b]	11.7[b]
Bt_1	54.4[a]	28.0[b]	4.6[b]	6.9[b]	51.2[b]	69.5[a]	3.4[c]	5.4[c]
Bt_2	31.8[a]	30.5[a]	3.0[b]	5.3[b]	39.6[a]	26.9[b]	3.3[c]	4.2[c]
C_1	39.3[b]	60.3[a]	14.6[c]	14.0[c]	43.2[a]	49.1[a]		
C_2	29.4[ab]	33.3[a]	7.6[c]	12.3[bc]				

† Within horizons and dates, means followed by the same letter are not significantly different according to Fisher's $LSD_{0.05}$.

of the 16 plots. The block effect for total C was pronounced ($P < 0.001$), with carbon contents 35% greater in block 2 than in block 4. A decreasing trend in total carbon contents was observed in the Ap horizon of the B treatment from 1.01% in June 1995 to 0.90% in October 1996. Nevertheless, this variation proved to be non significant. Angers (1992) reported that a minimum of three years were necessary to observe significant differences in SOM contents between alfalfa and bare soil plots.

Deep samples, taken to depths of 150 cm on 14 May and 12 October 1996, revealed increased total carbon contents in the Bt_1 and Bt_2 horizons for A and AS treatments and decreased C contents for B and BS treatments (Table 1.6). Total carbon, nitrogen and C/N ratios were not significantly affected by treatments in May 1996. By Fall 1996, carbon contents in the Bt_1 horizon of AS plots were significantly higher than in BS plots (Table 1.6). Soil C/N ratio in the Bt_1 horizon of BS plots was significantly lower than in any other plots. Soil nitrogen contents were lower in the Bt_2 horizon of BS plots than in any other plots (Table 1.6). Factorial analysis for October 1996 showed total carbon contents and C/N ratios of the Bt_1 horizon to be significantly higher under living alfalfa stand than under bare fallow soils, wether shoots were applied or not (data non reported). These results suggest that alfalfa root systems have a substantial impact on SOM levels below the Ap horizon.

Total amounts of soil organic carbon in the Ap, Bt_1 and Bt_2 horizons were computed by the formula:

$$\text{Total C (kg ha}^{-1}) = \sum^{\text{horizons}} 10000\ (\text{m}^2\ \text{ha}^{-1}) \times \text{depth (m)} \times \text{BD (kg m}^{-3}) \times \text{C (\%)} / 100$$

Table 1.6. Soil carbon and nitrogen contents in the Bt_1 and Bt_2 horizons of soils under bare fallow (B), bare fallow with alfalfa shoot mulch (BS), alfalfa (A) and alfalfa with alfalfa shoot mulch (AS), after two years of treatment.

	Total Carbon		Total Nitrogen		C/N Ratio	
	Bt_1	Bt_2	Bt_1	Bt_2‡	Bt_1	Bt_2
	%					
B	0.299[ab†]	0.186[a]	0.0340[a]	0.0240[a]	8.73[a]	7.60[a]
BS	0.295[b]	0.171[a]	0.0348[a]	0.0233[b]	8.47[b]	7.58[a]
A	0.321[ab]	0.235[a]	0.0350[a]	0.0270[a]	9.18[a]	8.64[a]
AS	0.347[a]	0.265[a]	0.0375[a]	0.0300[a]	9.22[a]	8.74[a]

† Within horizons, means followed by the same letter are not significantly different according to Fisher's $LSD_{0.05}$.
‡ Significant differences unequally spaced due to missing data.

with BD = bulk density, and C = soil carbon,

Applied to B plots, this formula leads to 57,632 kg C ha^{-1} and 55,885 kg C ha^{-1} on 14 May and 12 October 1996, respectively. Consequently, the mineralization rate of the soil organic matter, inferred from the decrease in total carbon over time, was of 3.0% from May to October 1996. Mineralization rates of the SOM were also computed from the amount of nitrogen mineralized in the bare fallow plots. SOM mineralization was the only source of mineral nitrogen in the soil profile of B plots, excluding atmospheric deposition. Total soil nitrogen mineralized in the Ap, Bt_1 and Bt_2 horizons (top 70 cm) of B plots from 14 May to 12 October 1996 was assessed at 153.9 kg ha^{-1}, as mentioned at the end of the previous section. Average C/N ratio of SOM in B plots was of 9.9, as adjusted to respective amounts of SOM in Ap, Bt_1, and Bt_2 horizons. Consequently, total amount of soil organic carbon corresponding the mineralized nitrogen was of 1532 kg C ha^{-1}. This value, compared to total soil carbon contents, corresponds to a SOM mineralization rate of 2.6%. Consequently, difference in soil organic carbon contents and assessment of mineralized N by suction lysimeters and soil extractions gave comparable results with respect to mineralization rates of the soil organic matter. These results are similar to evaluations made by Barber (1979), who assessed, in a six-year field study, that 2.4 % of bare fallow soil SOM is lost to mineralization, annually, from a Raub silt loam in Indiana.

Denitrification

Denitrification rates, measured on 16 June 1996, were higher when alfalfa shoots were applied to bare soils and alfalfa plots (Table 1.7). This increase is consistent with other studies reporting higher denitrification rates following fresh residues application (Avalakki et al., 1995). Average denitrification rates doubled from treatment B (76 g N ha d^{-1}) to treatment A (159 g N ha d^{-1}). Alfalfa shoot application increased denitrification of bare soil and alfalfa treatments on 16 June 1996 by a similar factor of about 250 g N ha d^{-1}. Denitrification is a temporally and spatially very variable processus (Tiedje et al., 1989), rendering the conversion of these results into kilos of nitrogen lost over the season difficult. The data are in a reasonable range of denitrification values. Van Kessel et al. (1993) reported an average denitrification rate of 331 g N ha^{-1} d^{-1} in a pea field during the month of June in Saskatchewan.

Table 1.7. Denitrification rates of bare fallow (B), bare fallow with alfalfa shoot mulch (BS), alfalfa (A) and alfalfa with alfalfa shoot mulch (AS), on 16 June 1996. Depth 0-15cm.

Treatments	Denitrification Rates
	g N_2O-N ha^{-1} d^{-1}
B	76 (26) ^{c†}
BS	323 (180) ^{ab}
A	159 (122) ^{bc}
AS	419 (289) ^{a}

† Mean (median) with the same letter are not significantly different at $P \leq 0.05$.

CONCLUSIONS

Alfalfa shoot mulch application to surface soil of alfalfa plots resulted in a 44% increase in nitrogen exports from herbage yields, for the second growing season. Denitrification rates were doubled, and soil-incorporated organic debris presented significantly higher N contents, when shoot mulch was applied to alfalfa plots. Amounts of nitrogen stored in crowns and roots of alfalfa, soil organic matter, and soluble and extractable soil mineral nitrogen pools were not significantly modified by shoot mulch application to alfalfa plots. These findings suggest that supplemental organic nitrogen inputs in alfalfa systems on Kalamazoo loam soils do not result in enhanced leaching but are exported through increased herbage N contents and soil denitrification rates.

Alfalfa and bare fallow soils responded very differently to alfalfa shoot mulch application. Mulch decomposition rates were enhanced by living alfalfa stands compared to bare fallow soils. Soluble and extractable mineral N contents were kept at very low levels under living alfalfa stands, whether shoot mulch was applied or not. Suction lysimeter and soil extraction data showed evidence of very little leaching under alfalfa stands. This study suggests that most of the nitrogen applied as shoot mulch was directly recycled into shoot biomass, accompanied by a probable decrease in dinitrogen fixation. Significant contribution of alfalfa stands to SOM levels could only be shown in the Bt_1 horizon. This suggests a high activity of alfalfa roots and soil microbes in the Bt horizons, and possibly leaching of dissolved organic matter.

Alfalfa shoot mulch application to surface soil of bare fallow plots significantly modified soluble and extractable mineral N distributions within the soil profile. While alfalfa shoot mulch promoted higher mineral N contents under bare fallow during Summer and Fall, data suggest that increased leaching under mulch reduced soil mineral N contents during Winter and Spring. Application of alfalfa mulch to bare soil did not increase SOM levels. Mineral nitrogen generated by decaying alfalfa shoots did not accumulate in the profile of bare fallow soils due to increased leaching and denitrification losses. This study suggests that late summer application of legume mulch can result in lesser amounts of soluble mineral N in the top of the soil profile by mid-spring of the following year, due to enhanced leaching and denitrification losses.

Mineralization of the SOM under bare fallow produced mineral nitrogen in excess of 150 kg N ha^{-1} from May to October of the second growing season, corresponding to SOM mineralization rates of 2.6%. A similar SOM mineralization rate (3.0%) was calculated from SOM loss over the same period of time.

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mineral N analyses. John Fergusson is thanked for his precious help in the making and installing of TDR and minirhizotron probes. Jane Boles is gratefully thanked for analyzing denitrification samples on the gas chromatograph.

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CHAPTER 2

Influence of Alfalfa Root Systems and Shoot Mulch on Soil Hydraulic Properties and Soil Aggregation.

ABSTRACT

Effects of contrasted root system and mulch conditions on soil water and physical properties were monitored in a Kalamazoo loam soil (fine-loamy, mixed, mesic Typic Hapludalf). A field experiment was conducted at the Long-Term Ecological Research site at the Kellogg Biological Station in southwestern Michigan from December 1994 to December 1996. Four treatments were considered: bare fallow (B), bare fallow with alfalfa (*Medicago sativa* L.) shoot mulch (BS), alfalfa (A), and alfalfa with alfalfa shoot mulch (AS). Frequent measurements of volumetric soil water contents were conducted in the Ap, Bt_1 and Bt_2 horizons by time domain reflectometry (TDR), from early spring to late fall of each year. Fine root development in A and AS treatments were monitored by minirhizotron technology. Undisturbed soil samples and aggregates were collected for analyses of physical properties in October 1996. Alfalfa root systems increased saturated hydraulic conductivities (K_s) total and macroporosities, and water recharge rate of the soil profile. Saturated hydraulic

conductivities were highly correlated to macroporosities (r = 0.90) and porosities at field capacity (r = 0.91). Total porosities were significantly influenced by soil carbon and total root numbers. Mulch application had little effect on the distribution of alfalfa root systems in the soil profile. Aggregate stability (0-20 cm) was significantly enhanced by alfalfa shoot mulch application, but not significantly modified by alfalfa root systems. Mean weight diameter of aggregates from surface 20 cm of bare fallow soils were increased by an excess of 20% with application of alfalfa shoot mulch.

INTRODUCTION

Plant root systems and crop residue management modify soil physical properties, affecting retention and movement of water in soils (Prasad and Power, 1991; Smucker et al., 1995). Part of the rotation effect of legume crops has been attributed to improved soil physical properties (Folorunso et al., 1992, McVay et al., 1989). Though this improvement results from a combination of effects from above and below ground plant materials, few studies have discriminated for their respective contributions. In this study, the influences of alfalfa (*Medicago sativa* L.) roots and shoots on soil physical properties and water movement in the root zone were investigated over a two year period in a Kalamazoo loam soil (fine-loamy, mixed, mesic Typic Hapludalf) in southwestern Michigan.

Improved soil structural stability under alfalfa stands have been reported

by several authors (Angers, 1992; Perfect, 1990; Chantigny et al., 1997). Alfalfa root systems have been reported to increase the saturated hydraulic conductivity of soils free of previous root channels (Li and Ghodrati, 1994). Meek et al. (1992) observed a six-fold increase in the hydraulic conductivity (K_s) of compacted sandy loam when planted with alfalfa. Mitchell et al. (1995) reported that, contrary to wheat, alfalfa root systems have the ability to increase the saturated hydraulic conductivity of swelling soils.

Mulch application to bare fallows reduces water losses from the soil profile (Prasad and Power, 1991; Steiner, 1994; Walsh et al., 1996). Surface application of residues is more efficient than incorporation for soil water conservation (Duley and Russel, 1939; Prasad and Power, 1991). Little information is available on mulch effects on saturated hydraulic conductivity. Lal et al. (1980) reported significant increases in K_s by mulch application on recently cleared tropical Alfisols. Prasad and Power (1991) estimate that mulching is likely to increase K_s due to higher soil faunal activity.

MATERIAL AND METHODS

Experimental Design and Treatments

A field experiment was conducted at the NSF-supported Long-Term Ecological Research (LTER) site at the Kellogg Biological Station in southwestern Michigan. Four treatments were considered: bare soil (B), bare soil to which alfalfa shoots were applied after each harvest (BS), alfalfa with shoots

removed after each harvest (A), alfalfa with shoots applied to the soil surface after each harvest (AS). Each treatment was replicated four times in a randomized complete block design. Microplots, 6 by 10 m each, were installed in a Kalamazoo loam soil (fine-loamy, mixed, mesic Typic Hapludalf) in late August 1994. The preceding crop was corn, fertilized at 123 kg N ha^{-1}. Moldboard plowing was performed to a depth of 23 cm following corn harvest. All plots were tilled and trafficked equally. Alfalfa was drilled in half of the plots on 30 August 1994. The drill was driven across the bare soil plots without seeds. The bare soil plots were kept free of weeds by applications of glyphosate at approximately six-week intervals between April and August of each year. Plots received no nitrogen fertilizers. Potash was applied at a rate of 280 kg ha^{-1} of K_2O equivalents, together with 2.2 kg ha^{-1} of boron, on 13 June 1996. Lime was applied at a rate of 2.5 t ha^{-1} on 14 June 1996. The alfalfa plots were harvested 3 times in each of the 1995 and 1996 growing seasons. At harvest, alfalfa plants were cut 5 cm above the soil by a 90 cm wide sickle-bar mower. After cutting, the alfalfa shoots were raked from the A and AS plots. Equal volumes of alfalfa shoots were then applied to all AS and BS plots. A one meter ineffective border was considered around each plot. The remaining surface within each plot was allocated to: 1) non destructive sampling with *in situ* instruments (2 x 4 m), 2) yield assessment (4 x 4 m), and 3) destructive sampling (2 x 4 m). Plots were separated by a surface plastic barrier, protruding 5 cm from the ground to prevent possible run-off/run-on between plots.

Measurements

Volumetric soil water contents were assessed by time domain reflectometry (TDR) measurements. Each plot was equipped with TDR probes (28.5 cm-long) inserted at 15, 35 and 60 cm to intercept the Ap, Bt_1 and Bt_2 horizons. Probes were inserted horizontally in a small profile dug in every plot before planting. Soil profiles were described and used for horizon delineation. The profiles were recompacted horizon by horizon and the cable buried before planting. Soil moisture data were collected with a TDR-meter model 1502C (Tektronix Inc, Beaverton, OR). Transformation of TDR readings into volumetric water contents was performed using Topp's equation (Topp et al., 1980). Alfalfa root system development was monitored by minirhizotron technology (Ferguson and Smucker, 1989; Upchurch and Ritchie, 1983). Three 2.40 m long polybutyrate minirhizotrons tubes (MR) were installed at a 45° angle in every A and AS plot. One control MR tube was placed in every B and BS plot. Minirhizotron pictures were recorded three times a year with a minirhizotron color camera (Bartz Technology, Santa Barbara, CA).

Four undisturbed soil cores per plot were collected in October 1996 for saturated hydraulic conductivity (K_s), bulk density (BD), and porosity analyses. Cores, 7.6 x 7.6 cm, were collected on the soil surface, with the top 0.5 cm of soil and residues gently scraped away. Cores were saturated for 48 hours prior to K_s measurements conducted by the constant head method (Klute and Dirksen, 1986). After re-saturation, cores were placed in pressure chambers at

0.006 and 0.033 MPa for 4 days, corresponding to macroporosity and field capacity (FC) tensions. Cores were oven dried for 48 hours at 105°C for bulk density determination.

Soil samples were collected in October 1996 for soil aggregate stability analyses by the wet sieving technique (Kemper and Chepil, 1965). Four subsamples (0-20 cm) were collected from each plot, combined in the field, and air dried. Samples were sieved to obtain the 4.75-6.30 mm fraction used for wet sieving (Sissoko and Smucker, 1997).

Statistical Analyses

Statistical analysis of single date data sets were conducted using the general linear model of the SAS system (SAS Institute, 1989). Data were first analyzed considering four individual treatments, with means and Fisher's least significant differences ($LSD_{0.05}$) reported. In a second step, the four treatments were grouped into a 'plant' factor, i.e. presence or absence of a living alfalfa stand, and a 'mulch' factor, i.e. application or no application of alfalfa shoot mulch at harvest. Saturated hydraulic conductivity data were proven to not be normally distributed according to the normality test and histograms of the univariate procedure of the SAS system (SAS Institute, 1989). Logarithmic transformation of the Ks data fitted normal distribution. Consequently, mean separation tests were performed on log-transformed data, with medians of the non-transformed data set reported.

Data set including four or more sampling dates were analyzed using univariate repeated measures techniques with a spatio-temporal correlation structure based on the mixed procedure of the SAS system (Gregoire et al., 1995; Littell et al., 1996; Schabenberger and Gregoire, 1995). This analysis permits inference on main effects, simple effects, and interactions between treatments and treatments by time while simultaneously accounting for the fact that repeated observations on the same experimental unit are not independent. Since measurements were collected at three depths at every given point in time correlations over time at a given depth and across depth at a given time needed to be incorporated. Time and depth were considered as discontinuous variables, which gave best values for model fitting criterions for both root and soil water measurements. Thorough investigation of various candidate correlation models resulted in the choice of an exponential correlation model where distance between location is measured as Euclidean distance in time and depth. The treatment structure was established as a 2 x 2 factorial with factors 'plant' and 'mulch' to gain further insight into the interaction structure. Volumetric soil water content data set, including more than 40 recording dates, turned out to be too variable over time to be meaningfully analyzed as one entity. Periods of continuous soil drying or wetting, including 4 or 5 individual sampling dates, were analyzed separately to detect significant treatment differences and interactions.

RESULTS AND DISCUSSION

Volumetric Soil Water Contents

Fluctuations in volumetric soil water contents were, as expected, higher in the upper soil horizons than for deeper horizons, in both 1995 (Figure 2.1) and 1996 (Figure 2.2). Shoot application to soils under living alfalfa stands appeared to have little impact on soil water contents (Figures 2.1 and 2.2). Fluctuations of soil water contents were of greater amplitude under alfalfa stands than bare fallows (Figures 2.1 and 2.2). Soil drying and wetting rates were significantly modified by the presence of living alfalfa plant root systems, as expressed by the significant 'plant x date' interactions for individual soil wetting and drying periods (Table 2.1). Application of shoot mulch did not significantly modify soil wetting or drying rates, as shown by non significant 'mulch x date' interactions (Table 2.1). No overall mulch effect could be observed (Table 2.1). Minimum soil water contents at the end of dry periods were significantly lower in the Ap horizons of A and AS plots than of B and BS plots (Figure 2.3). Shoot application did not significantly modify volumetric soil water contents under alfalfa stands during dry periods. Volumetric soil water contents of the Ap horizon of bare fallow soils on 22 August 96 were significantly increased by shoot mulch application (Figure 2.3). This suggests that by the end of the second growing season the accumulated amounts of applied mulch were sufficient to augment soil water contents in the Ap horizon.

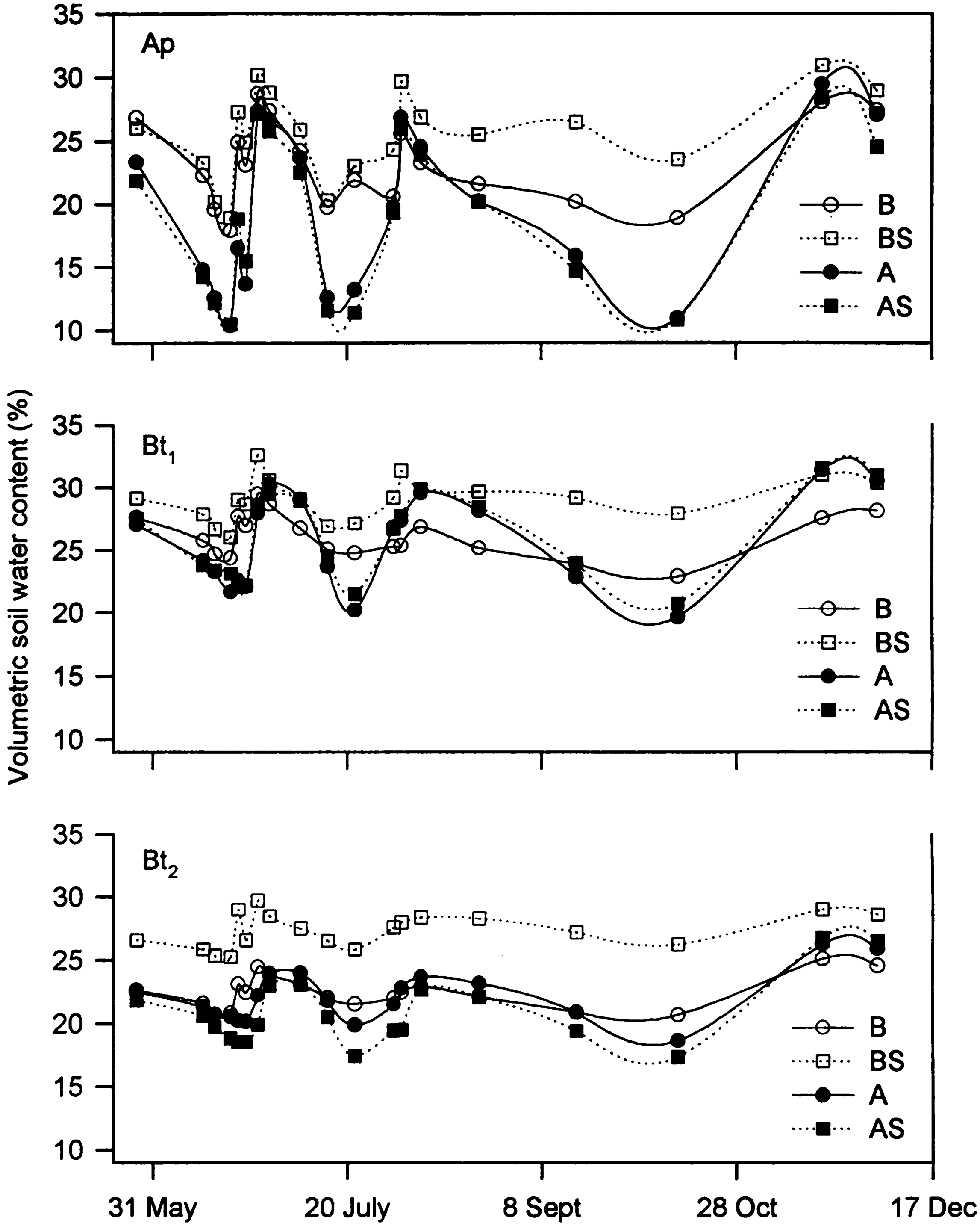

Figure 2.1. Volumetric soil water contents in the Ap, Bt_1 and Bt_2 horizons of soils under bare fallow (B), bare fallow with alfalfa shoot mulch (BS), alfalfa (A), and alfalfa with alfalfa shoot mulch (AS), in 1995.

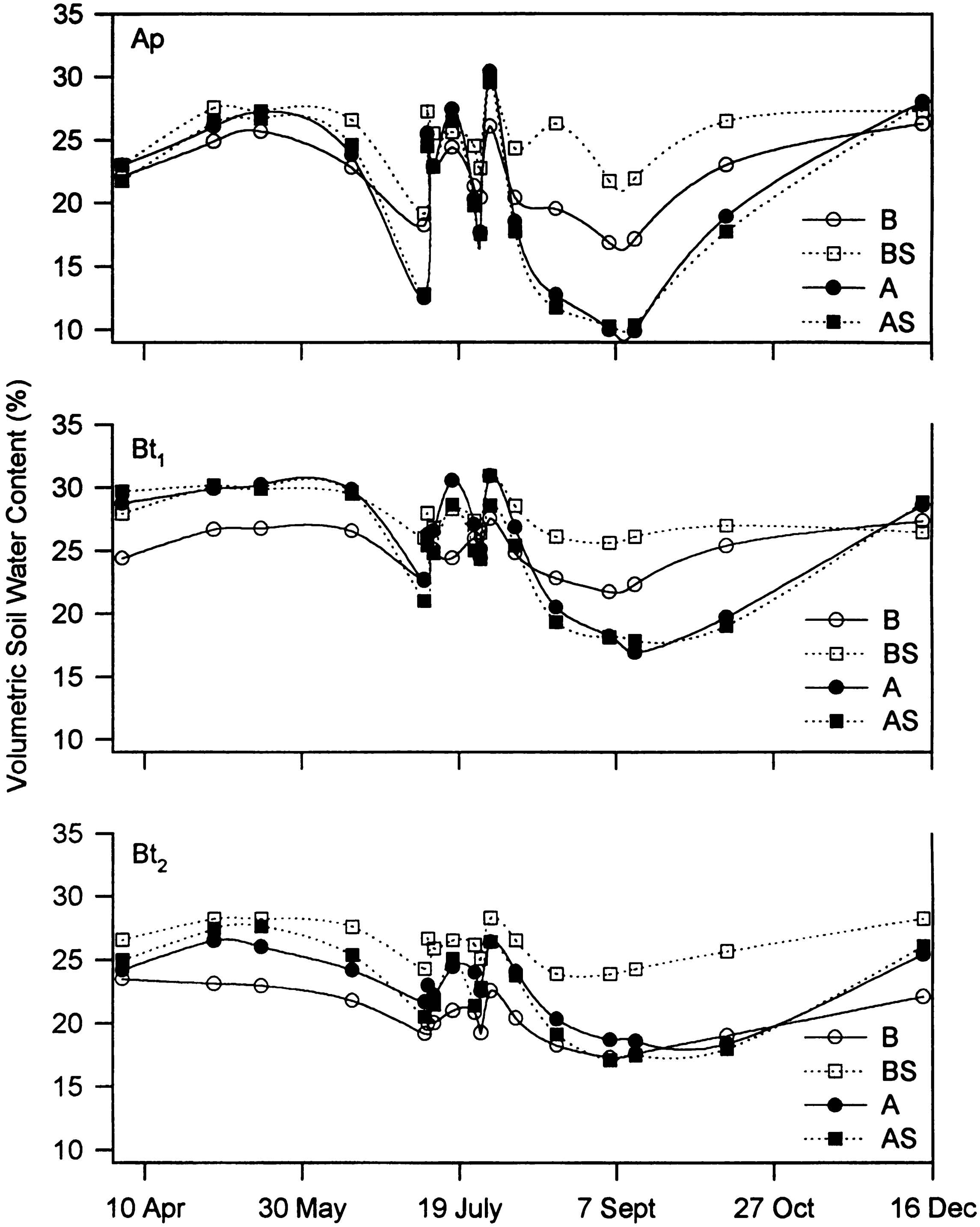

Figure 2.2. Volumetric soil water contents in the Ap, Bt_1 and Bt_2 horizons of soils under bare fallow (B), bare fallow with alfalfa shoot mulch (BS), alfalfa (A), and alfalfa with alfalfa shoot mulch (AS), in 1996.

Table 2.1. Living alfalfa stand (plant factor) and shoot mulch (mulch factor) modifications of volumetric soil water contents for two drying and one wetting period.

Source of Variation	Drying Period Aug - Oct 95	Wetting Period June - July 96	Drying Period July - Sept 96
Plant	NS†	NS	*
Mulch	NS	NS	NS
Depth	**	*	**
Date	***	***	***
Plant x Mulch	NS	NS	*
Plant x Depth	NS	NS	NS
Plant x Date	***	***	***
Mulch x Depth	NS	NS	NS
Mulch x Date	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, respectively.
† NS = non significant ($P > 0.05$).

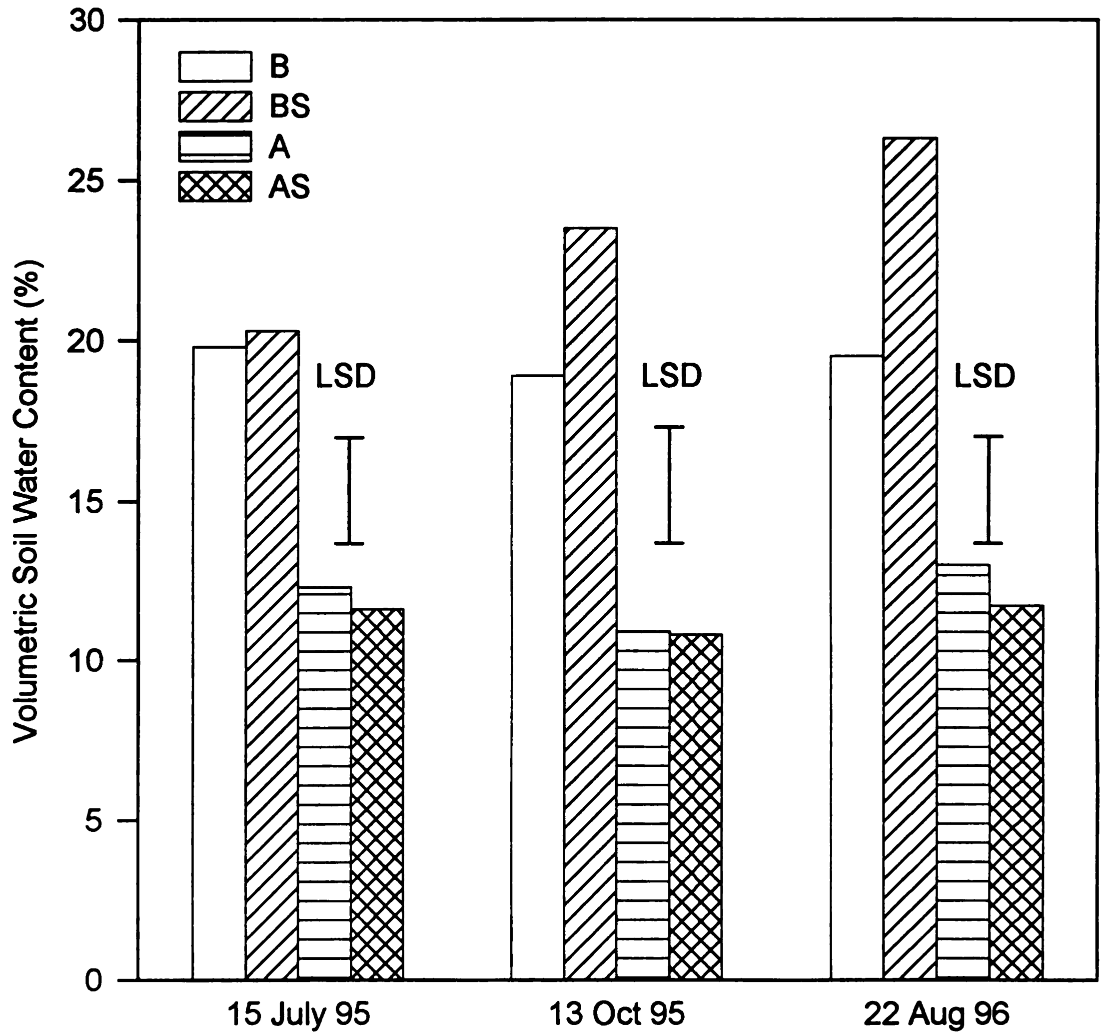

Figure 2.3. Volumetric soil water contents in the Ap horizon of soils under bare fallow (B), bare fallow with alfalfa shoot mulch (BS), alfalfa (A), and alfalfa with alfalfa shoot mulch (AS), at the end of three dry periods. LSD = Fisher's least significant difference at $P \leq 0.05$.

Root Systems Distribution

By the end of the second growing season, alfalfa fine roots colonized the soil profile fairly uniformly from depths of 50 to 120 cm (Figure 2.4). Substantial root numbers were present at maximum sampling depth of 140 cm in September 1996 (Figure 2.4), which confirms previously reported limitations of minirhizotron technology in alfalfa stands older than two years (Pietola and Smucker, 1995). High root turnover rates were observed in the surface 9.5 cm, where root death exceeded 75 and 50% during the 1995 and 1996 growing seasons respectively (Figure 2.5). Greatest fine root mortalities in the upper 10 cm of soils under alfalfa stands were previously reported (Goins and Russelle, 1996). The high rate of root mortality in the uppermost soil layer appears to result from the large fluctuations of soil water contents affecting the Ap horizon (Figures 2.1 and 2.2), where several several times volumetric soil water contents dropped below 15% at depths of 15 cm. Such lows were never observed in deeper horizons. Alfalfa root turnover rates were not significantly modified by mulch treatments in all soil horizons (data no reported). Application of alfalfa shoot mulch did not significantly alter total alfalfa fine root numbers on any given date. Repeated measures analysis over time and depth revealed 'treatment x depth x date' as sole significant source of variation relative to treatment. This indicates that fine root distribution in the soil profile was affected by treatment but not consistently through depth at any given date or over time for any given depth. Several investigators reported the absence of significant difference

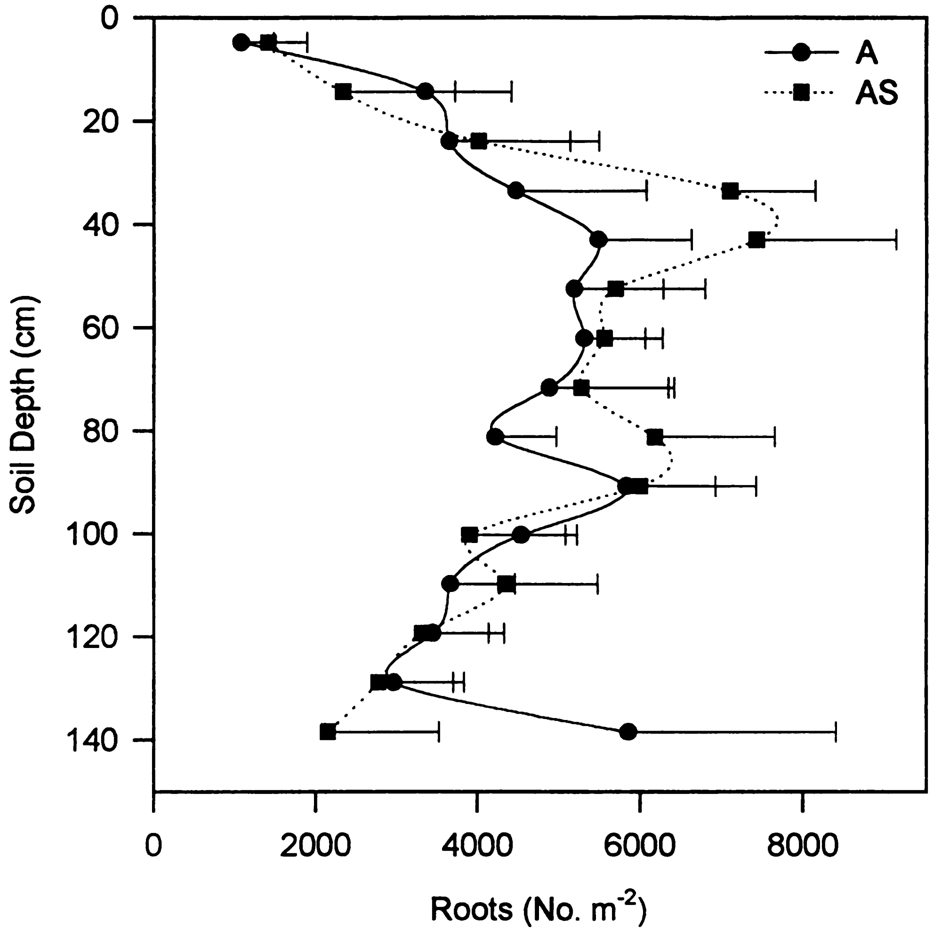

Figure 2.4. Minirhizotron observations of fine root profiles in alfalfa plots with shoots removed (A), and with alfalfa shoot mulch applied (AS), on 20 September 1996. Standard errors given for n = 4.

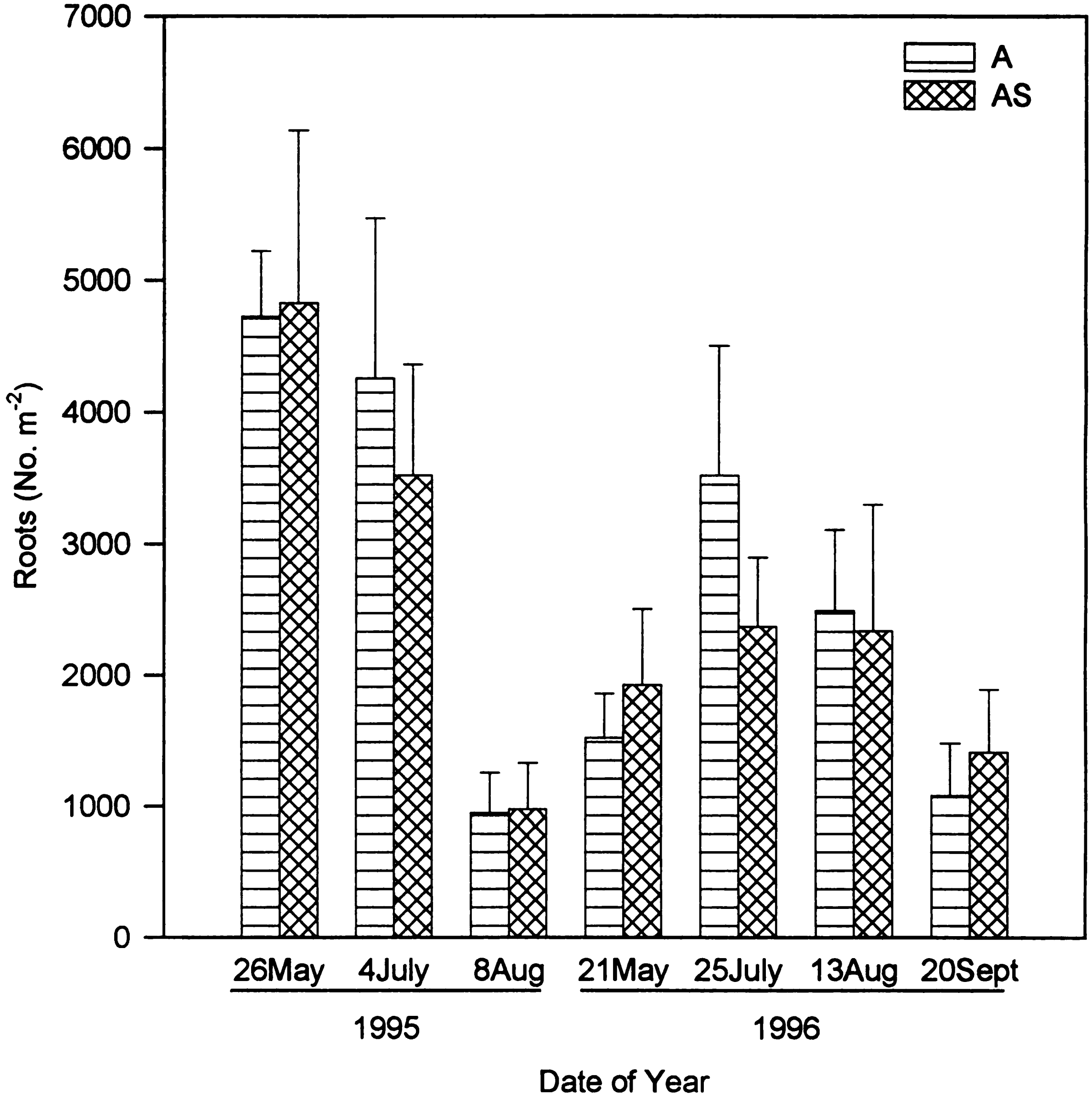

Figure 2.5. Minirhizotron root counts in the upper 9.5 cm of alfalfa plots with shoots removed (A), and with shoot mulch applied (AS).
Standard errors given for n = 4.

between alfalfa root production of nodulating and non-nodulating alfalfa varieties, as monitored by minirhizotron technique (Goins and Russelle, 1996) and root extractions (Blumenthal and Russelle, 1996; Goins and Russelle, 1996; Lory et al., 1992). These findings suggest that the development of the alfalfa root system is not modified by the availability of nitrogen to the crop, which explains the lack of root response to increased mineral nitrogen availability observed under decaying alfalfa shoot mulches. In addition, soil water contents under alfalfa stands were not significantly modified by shoot mulch application. Soil temperatures, at three depths, recorded at five dates in 1995, showed no significant difference between mulched and non-mulched alfalfa plots, while pronounced differences were observed between B and A plots and between B and BS plots (data not reported). Larsson and Jensén (1996) reported that root populations of black current bushes (*Ribes nigrum*) were significantly modified by mulch application, resulting mainly from increased soil water contents under mulch. In conclusion, alfalfa shoot mulch application did not significantly modify soil water contents and temperatures resulting in unmodified distributions of alfalfa root systems.

Soil Physical Properties

Total, and macro and field capacity soil porosities were significantly modified by alfalfa root systems, but not by shoot application (Table 2.2). Highest total and macroporosities were observed in the A treatment (Table 2.3). Lowest

Table 2.2. Factorial analyses for plant and mulch affects on the of log-transformed saturated hydraulic conductivities (K_s), bulk densities (BD), mean weight diameter (MWD), total porosities, macro and micro porosities and porosities at field capacity (FC), after two years of treatment.

Source of Variation†	K_s	BD	MWD	Porosity			
				Total	Macro	@ FC	Micro
Plant	***	NS‡	NS	*	*	*	NS
Mulch	NS	NS	**	NS	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, respectively.
† Plant x Mulch interactions non-reported (all non-significant).
‡ NS = non significant ($P > 0.05$).

Table 2.3. Saturated hydraulic conductivities (K_s), bulk densities (BD), mean weight diameter (MWD), total, macro, and micro porosities, and porosities at field capacity (FC) in soils under bare fallow (B), bare fallow with alfalfa shoot mulch added (BS), alfalfa (A), and alfalfa with alfalfa shoot mulch added (AS), following two years of treatment.

	K_s†	BD	MWD	Porosity			
				Total	Macro	@ FC	Micro
	cm hr^{-1}	Mg m^{-3}	mm	%			
B	1.14^{b‡}	1.46^{a}	3.76^{b}	38.7^{b}	11.4^{ab}	13.9^{ab}	27.3^{b}
BS	0.86^{b}	1.49^{a}	4.57^{a}	39.0^{ab}	10.0^{b}	12.5^{b}	29.0^{a}
A	1.64^{a}	1.45^{a}	4.26^{a}	41.0^{a}	13.0^{a}	15.3^{a}	27.9^{ab}
AS	1.50^{a}	1.46^{a}	4.56^{a}	40.1^{ab}	12.0^{ab}	14.8^{a}	28.1^{ab}

† Median reported, means separation test conducted on log-transformed data.
‡ Same letters indicate non-significant differences by Fisher's $LSD_{0.05}$.

total and macroporosities were observed in the B and BS treatments, respectively (Table 2.3). Porosity at field capacity, i.e. total porosity minus water content at field capacity, was significantly increased by alfalfa root systems (Table 2.2). Bare fallow soils developed higher micro porosity when shoot mulch was applied (Table 2.3). Bulk densities (BD) were not significantly affected by treatments (Tables 2.2 and 2.3), which agrees with other studies reporting that soil bulk densities are generally not modified by residue management or mulch application (Acharya and Sharma, 1994; Walsh et al., 1996).

Total porosities were correlated to total soil carbon contents and root numbers in the Ap horizon (Figure 2.6). Total soil carbon and root numbers independently influenced total porosity, which is reflected by the improved coefficient of correlation when both factors are considered in the regression (Figure 2.6) and by the absence of significant correlation between total soil carbon and root numbers (data not reported).

Saturated hydraulic conductivities (K_s) were significantly increased by alfalfa root systems (Table 2.2). These results confirm the direct contributions of alfalfa root systems to increased soil K_s, as previously reported by several authors (Caron et al., 1996; Li and Ghodrati, 1994; Meek et al., 1992; Mitchell et al., 1995). Lowest K_s were observed in the BS treatment, which also presented lowest macroporosity (Table 2.3). Hence, saturated hydraulic conductivities were significantly correlated to macroporosities (Figure 2.7A). The correlation was even more pronounced for K_s vs. field capacity porosity (Figure 2.7B). A significant positive correlation of 0.57 was observed between K_s and root

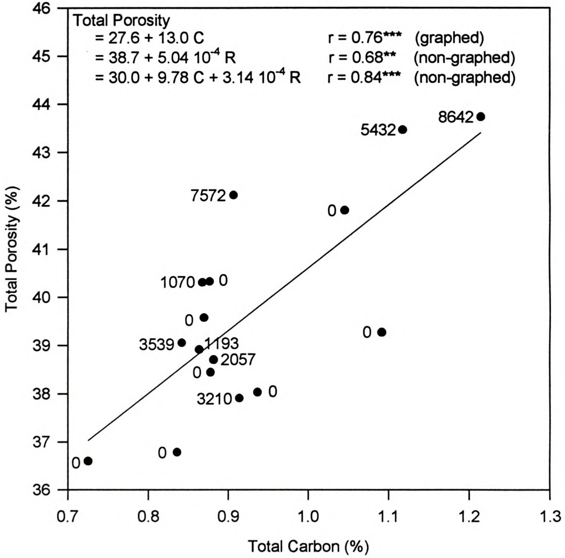

Figure 2.6. Regression of total porosity vs. total carbon (C) in the Ap horizon of bare fallow and alfalfa plots with and without shoot mulch application, after two years of treatment. Root numbers per m^{-2} (R) indicated next to data points.

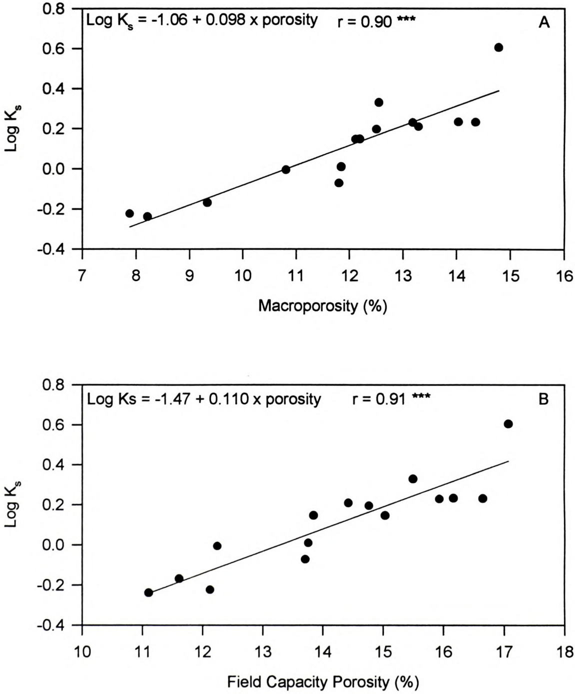

Figure 2.7. Regression of log K_s vs. macroporosity (graph A) and field capacity porosity (graph B), for the surface 10 cm of plots under bare fallow and alfalfa stands. One outlier removed from each graphics.
*** Significant at $P < 0.001$.

turnover rates in the upper 10 cm of the soil profile in 1995 (data not reported). No significant correlation was found with total root numbers in 1996, which indicates that root death and disappearance rates have a higher impact on K_s than living root density. Opposite to 1995 root turnover rates, no significant correlation was observed between 1996 root turnover rates and K_s, indicating that a response time was necessary for root death to influence K_s. This delay was probably required for sufficient decomposition of root tissues to create empty root induced macropores (RIMs). Meek et al. (1992) reported that root channels or RIMs have to be devoid of alfalfa root tissues for contributing to the preferential flow of water through soils. Alfalfa root systems can potentially continue to increase water flow through the soil profile for an extended period of time after killing the stand. However, the developing root system of the succeeding crop can plug the empty RIMS, reducing the effect of alfalfa RIMS, as suggested by several authors (Gish and Jury, 1983; Rasse and Smucker, 1997; Smucker et al., 1995).

Aggregate stability of the surface 0-20 cm of soil was significantly enhanced by applications of alfalfa shoot mulch, but not modified by the presence alfalfa root systems (Table 2.2). Nevertheless, when soils without alfalfa mulch are considered separately, alfalfa root systems significantly increased mean weight diameter of soil aggregates (Table 2.3). Although improved soil structural stability under alfalfa stands have been reported by several authors (Angers, 1992; Perfec et al., 1990; Chantigny et al., 1997), specific effects of shoots and roots have not been investigated. Chantigny et al.

(1997) reported that alfalfa promotes soil aggregation to a lesser extend than canary grass (*Phalaris arundinacea* L.) and timothy (*Pleum pratense* L.). Martens and Frankenberger (1992) observed higher improvement of the soil structural stability with incorporation of alfalfa straw than poultry manure and sewage sludge. Aggregate stability could not be significantly correlated with K_s, bulk density, porosity, total carbon, root numbers or root turnover rates (data not reported). This implies that aggregate stability was driven by other parameters, probably transient carbon pools such as soluble carbon compounds and microbial exudates, as identified in other studies (Haynes et al., 1991; Angers and Mehuys, 1989, Sissoko and Smucker, 1997). Degens et al. (1994) reported that the stabilization of macro aggregates by the enmeshing effect of clover roots in sandy soils appeared negligible. Our results support the hypothesis that soil aggregation under alfalfa stands is mainly driven by the amount of soluble carbon compounds incorporated into the soil. Consequently, alfalfa shoot mulch contributed more to the stability of soil aggregates than root systems due to its large input of low C/N ratio plant tissues.

CONCLUSIONS

Alfalfa root systems potentially increased water flow as indicated by higher saturated hydraulic conductivities, total and macroporosities, and water recharge rate of the soil profile. Modifications of saturated hydraulic conductivities appeared to directly reflect changes in macroporosity. Root turnover rates and disappearance had greater impacts on K_s than living root densities. A delay time between root death and enhanced K_s was observed, which was probably necessary for emptying root induced macropores of dead root tissues. Minirhizotron technology was successfully used for better understanding modifications of water flow in soils induced by growth and decay of crop root systems. It is also concluded that both living root systems and root history, i.e. turnover rates, should be considered in analyzing the impact of root systems on physical properties.

Aggregate stabilities were more affected by carbon sources from shoot mulch than root turnover. Further research should be conducted on above and below ground plant contributions to soil aggregation to design cover crop and residue management systems that best protect soil structure.

ACKNOWLEDGMENTS

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CHAPTER 3

Corn Yields and Soil Nitrogen Dynamics in a Corn - Alfalfa - Corn Succession.

ABSTRACT

Alfalfa contributions to corn yields and soil mineral nitrogen pools were studied under conventional tillage (CT) and no tillage (NT) systems over a three year corn, alfalfa and corn succession. The field experiment compared CT vs. NT managements in fertilized and non fertilized Kalamazoo loam soils (fine-loamy, mixed, mesic Typic Hapludalf). Four of the non fertilized plots were equipped with undisturbed monolith lysimeters to monitor nitrate leaching.

Corn yields were not significantly affected by fertilization, when corn was planted shortly after spray-killing the alfalfa stands in the Spring. Soil mineral nitrogen under corn following alfalfa increased in excess of N fertilization from May to November 1996. Corn following corn in non fertilized systems produced nitrate leaching in excess of 20 kg NO_3-N ha^{-1} yr^{-1}. Living alfalfa stands kept nitrate leaching rates at very low levels. Nitrate concentrations exceeding EPA standards of 10 mg l^{-1} were observed for deep leaching soil solutions in the winter following unfertilized corn harvest, nine months after spray-killing the alfalfa crop. Alfalfa plant tissue decomposition contributed to soil mineral N pools

as high as 115 kg N ha^{-1}, within the first six months following the spray-killing of the stand. The mineral nitrogen released by decaying alfalfa plants reached a maximum concentration in the upper part of the soil profile 40 days after spray-killing the stand. These results, obtained for a dry growing season, indicate that best management practices for corn after alfalfa would be to kill the alfalfa stand in the spring, and to apply little or no nitrogen fertilizer at planting.

INTRODUCTION

Nitrogen-conservative agricultural systems are increasingly sought by agronomists and environmentalists. Nitrate leaching in soils under corn production depends on tillage systems and nitrogen fertilizer inputs. Corn nitrogen fertilization tends to generate nitrate leaching problems when applications are in excess of plant uptake (Angle et al., 1993; Gast et al., 1978). Gast et al. (1978) reported little nitrate leaching differences between corn fields receiving from 20 to 112 kg N ha^{-1}.

No-tilled (NT) soils present higher infiltration rates (Bissett and O'Leary, 1996; Dao, 1993), and higher drainage water flows (Huang, 1995; Randall and Iragavarapu, 1995; Weed and Kanwar, 1996) than conventional tillage (CT) soils. This difference is explained by the continuity of soil macropore networks, especially root-induced macropores, in NT soils (Comia et al., 1994; Lal and Vandoren, 1990; Reynolds et al., 1995; Waddell and Weil, 1996). Soil water leachates contain higher nitrate concentrations in CT vs. NT corn production systems (Randall and Ivaragarapu, 1995; Weed and Kanwar, 1996). Combining drainage flow and nitrate concentration, total nitrate losses by deep leaching are generally slightly higher for CT than NT soils, under corn production (Randall and Ivaragarapu, 1995; Weed and Kanwar, 1996).

Numerous studies (Hesterman et al. 1986a & 1986b, Barnes et al. 1978 & 1983, Groya and Sheaffer 1985) have reported the yield-increasing affects by alfalfa on the subsequent non-legume crop. Nitrogen replacement values of alfalfa to a succeeding corn crop were estimated to be from 90 to 125 kg N ha^{-1} (Bruulsema and Christie, 1987). Fox and Piekielek (1988) reported a total N replacement value for a three year old alfalfa stand followed by three years of consecutive corn to be of 167 kg N ha^{-1}. Nevertheless, the alfalfa nitrogen replacement values for succeeding corn crops is still underestimated or neglected by many farmers, resulting in wasted fertilizers and groundwater pollution problems (El-Hout and Blackmer, 1990; Peterson and Russelle, 1991).

Alfalfa has been reported to be beneficial as well as detrimental to the reduction of nitrate leaching losses. Lamb at al. (1995a) report that alfalfa has a great ability for absorbing nitrates at opportune moments of the year when nitrate pollution is a critical issue. The deep root system of alfalfa can recycle nitrates leached to depth inaccessible to other crops (Blumenthal and Russelle, 1996). On the other hand, mineralization bursts can lead to high levels of nitrate leached to the ground water if not timely matched by crop consumption (Cambell et al., 1994; Philipps and Stopes, 1995). This study was conducted to investigate the combined effects of tillage and fertilization on corn production and nitrate leaching, in a corn alfalfa corn succession.

MATERIAL AND METHODS

Experimental Design and Treatments

A corn alfalfa corn succession was studied from 1994 to 1996 as part of a long-term field experiment investigating nitrogen supply and tillage effects on soil-plant interactions. Field plots, 40 x 27 m each, were established in a randomized complete block design in 1986 in a Kalamazoo loam soil (fine-loamy, mixed, mesic Typic Hapludalf) at the Kellogg Biological Station in southwestern Michigan. Previous crop on these plots were corn in 1992 and 1993. Soil horizons are a loamy Ap from 0 - 0.25 m which overlays a clay loam Bt_1 from approximately 0.25 to 0.55 m, then a Bt_2 enriched in coarse material from approximately 0.55 to 0.80 m, which is underlain by a coarse glacial outwash parent material. Replicated treatments (n=4) consist 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). Undisturbed monolith lysimeters, 1.2 x 1.8 m of surface area and 2.1 m deep, were installed in two CT-NF and two NT-NF plots in 1990. Conventional tillage plots were moldboard plowed, and lysimeters manually spaded in the second week of April 1994. Roundup (glyphosate) was applied at rate of 7 liters per hectare on 03 May 1994. Corn (Pioneer hybrid 3573) was planted at 67,700 seeds per hectare in all plots and manually planted in lysimeters on 6 May 1994. Corn was planted at high density in the lysimeters and later thinned to guarantee a uniform plant density matching field conditions. Nitrogen fertilizer (ammonium-nitrate, 34-0-0) was applied to F plots in one application at rate of 123 kg ha^{-1} on 22 June 1994. Corn harvest was conducted by chopping the entire plants, on 23 August 1994. Total corn biomass per plot was recorded, and subsamples were taken for moisture content and total nitrogen analyses. Moldboard plowing, followed by a light discing was performed on all CT plots on 29 August 1994. Lysimeters under CT treatment were manually spaded. Roundup was sprayed on all NT plots and lysimeters at rate of 7 liters per hectare on 30 August 1994. Alfalfa (Pioneer 5246) was planted in all plots on 1 September 1994. All plots received 112 kg K_2O ha^{-1} and 337 kg ha^{-1} of pellet lime on 7 April 1995. Alfalfa was harvested three times in 1995; on 12 June, 22 July and 1 September. Total alfalfa biomass per plot were recorded at each harvest, and composite subsamples were taken for average plant moisture content. Alfalfa was spray-killed on 02 May 1996 with Roundup ultra at 4.6 l ha^{-1} and 2-4D ester at 2.3 l ha^{-1}. Conventional tillage plots were moldboard plowed and disced on 8 May 1996. Corn (Pioneer hybrid 3573) was drilled in all plots at rate of 67,700 seeds per hectare on 13 May 1996. Nitrogen fertilizer (ammonium-nitrate, 34-0-0) was applied to F plots in one application at rate of 123 kg ha^{-1} on 21 June 1996. Corn harvest was conducted by chopping the entire plants on 4 September 1996. Total corn biomass was recorded per plot, and subsamples were taken for total nitrogen analysis. Composite subsamples were taken for average plant moisture content. For all three years, lysimeters were harvested manually within a few days of field harvest. Total biomass per lysimeters was recorded and subsamples were taken for moisture content and total nitrogen analyses.

Instrumentation and Measurements

Each monolith lysimeter is equipped with a stainless steel access chamber, which is positioned directly along the lysimeter and gives access to one full side of the monolith. Access ports for instrumentation were cut in the metal wall separating the monolith from the access chamber. Sampling of the soil solution was conducted by suction lysimeters containing ceramic tips (2.2 x 5 cm) (Soil Moisture, Santa Barbara, CA), inserted horizontally into the Bt_1, Bt_2 and C horizons. Each monolith lysimeter is equipped with a drainage outlet at the bottom of the soil profile. The drainage solution was collected in a 58 l graduated container, allowing for the measurement of instantaneous and cumulative drainage rates, with an accuracy of ± 1 l. Suction lysimeter extracts and drainage samples were analyzed for nitrate and ammonia using a QuickChem automated ion analyzer (Lachat Instruments, Milwaukee, WI). Soil water contents of each horizon were estimated by time domain reflectometry (TDR). TDR probes, inserted 29 cm into soil horizons at same depths as suction lysimeters, were composed of two metal rods, 30.5 cm long and 0.5 cm in diameter, installed horizontally at a spacing of 5 cm apart in the soil profile. Soil water data were collected with a TDR-meter model 1502C (Tektronix Inc, Beaverton, Oregon, U.S.A.). The Topp's equation was used for estimating soil water contents from TDR wave forms (Topp et al., 1980). Soil water measurements were conducted at every date of suction lysimeter sampling.

Destructive soil sampling of the main field plots was conducted to depths of 150 cm in spring and fall of 1996 with a Giddings hydraulic probe of 7.5 cm core diameter (Giddings Machines Co., Ft. Collins, CO). Two cores were extracted from each plot and visually divided into Ap, Bt_1, Bt_2, C_1 and C_2 horizons. Gravimetric soil water contents were determined on subsamples oven dried for 24 hours at 105 °C. Field moist 20 g subsamples were extracted for NO_3-N and NH_4-N by shaking for one hour in 50 ml of 1 N KCl solution. Clear solutions were extracted by filtration through a Whatman No.1 filter and analyzed for NO_3-N and NH_4-N with a QuickChem automated ion analyzer .

Plant materials were oven dried at 70°C for moisture content. Finely ground ($\leq$ 0.5 mm) subsamples (0.150 g) were digested using standard total Kjeldahl procedures (Brenmer and Mulvaney, 1982). Total mineralized nitrogen, as ammonium in solution, was analyzed by a QuickChem automated ion analyzer.

Statistical Analyses

Statistical analyses were conducted using the general linear model of the SAS system (SAS institute, 1989). Field replicated measurements were analyzed using Fisher's least significant difference ($LSD_{0.05}$). Monolith lysimeter data, based on two sets of replicated measurements taken at multiple dates, were used to analyze temporal dynamics of soil mineral nitrogen. Error bars were represented by standard deviations, as standard errors of duplicated samples can be misleading with respect to the significance of mean separation.

RESULTS AND DISCUSSION

Corn Biomass Yields and Nitrogen Contents

Nitrogen fertilization significantly increased dry biomass (DB) yields of corn by 149% and 117% in CT and NT plots, respectively, in 1994 (Figure 3.1). Conventional tillage significantly increased DB yields of fertilized corn plant by 39% compared to no tillage, in 1994. Advantages of CT vs. NT management with respect to corn yields depend on soil type, amounts and distribution of the precipitations, and length of the growing season. Increased corn yields with CT compared to NT management were reported for poorly drained soils (Randall and Iragavarapu, 1995), while the opposite was observed in well drained soils (Angle et al., 1993). Late-planted corn, following plowed down or spray-killed cover crop, produced more under CT than NT managements in Wisconsin (Smith et al., 1992), but less in Kentucky (Zhang and Blevins, 1996). Delayed emergence and slower growth of NT compared to CT corn can constitute an obstacle to NT corn production in the northern Corn Belt (Carter and Barnett, 1987; Smith et al, 1992). No-tillage has been reported to promote higher soil water contents (Dao, 1993), however corn was not water-stressed in 1994

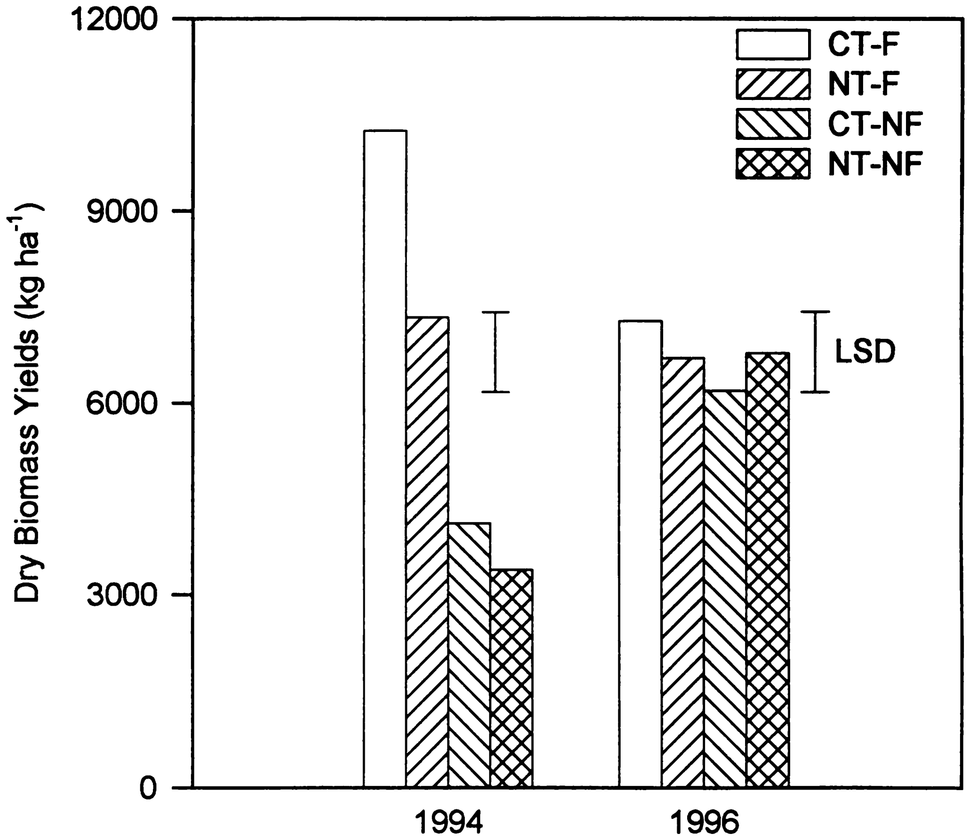


Figure 3.1. Corn plant dry biomass yields in 1994 and 1996, in conventional tillage (CT) and no tillage (NT) plots, with nitrogen fertilization (F) and with no nitrogen applied (NF).

(CERES-maize simulation, data not reported), which was an exceptionally wet year (913 mm), with precipitations amounting to 510 mm from 01 May to 31 August. Emerging corn plants were subjected to a frost in late May 1994. Visual estimation of the damages showed that corn plants in NT treatments had suffered more from the frost than CT plots. Apparently, the NT residue cover kept the heat from escaping the soil at night, which created cooler above-ground conditions, as suggested by Fortin (1993). Huang (1995) reported higher corn yields for Kalamazoo loam soils under NT than CT managements in 1991. Neither tillage nor fertilization treatments significantly modified corn DB yields in 1996. In conclusion, effects of tillage practices on corn yields for Kalamazoo loam soils in southwestern Michigan depend on temperature and precipitation conditions during the growing season.

Corn DB yields increased in 1996 by 50% and 100% in non fertilized CT and NT plots, compared to 1994 (Figure 3.1). Fertilized CT corn responded in the opposite direction in 1996 where yields were decreased by 29%. Lower yields than average were obtained for CT and NT fertilized corn in 1996 at different production sites of the Kellogg Biological Stations due to a prolonged summer drought (Robertson and Harwood, 1997; Harwood et al., 1997). Precipitation in July 1996 were exceptionally low compared to the previous years (Figure 3.2). Total precipitation for the period from May to August of 1994, 1995 and 1996 were of 513, 394 and 268 mm, respectively. Total herbage yields of 1995 alfalfa were not significantly affected by treatments for any of the three harvests conducted in 1995. Total amount of nitrogen contained in alfalfa shoots

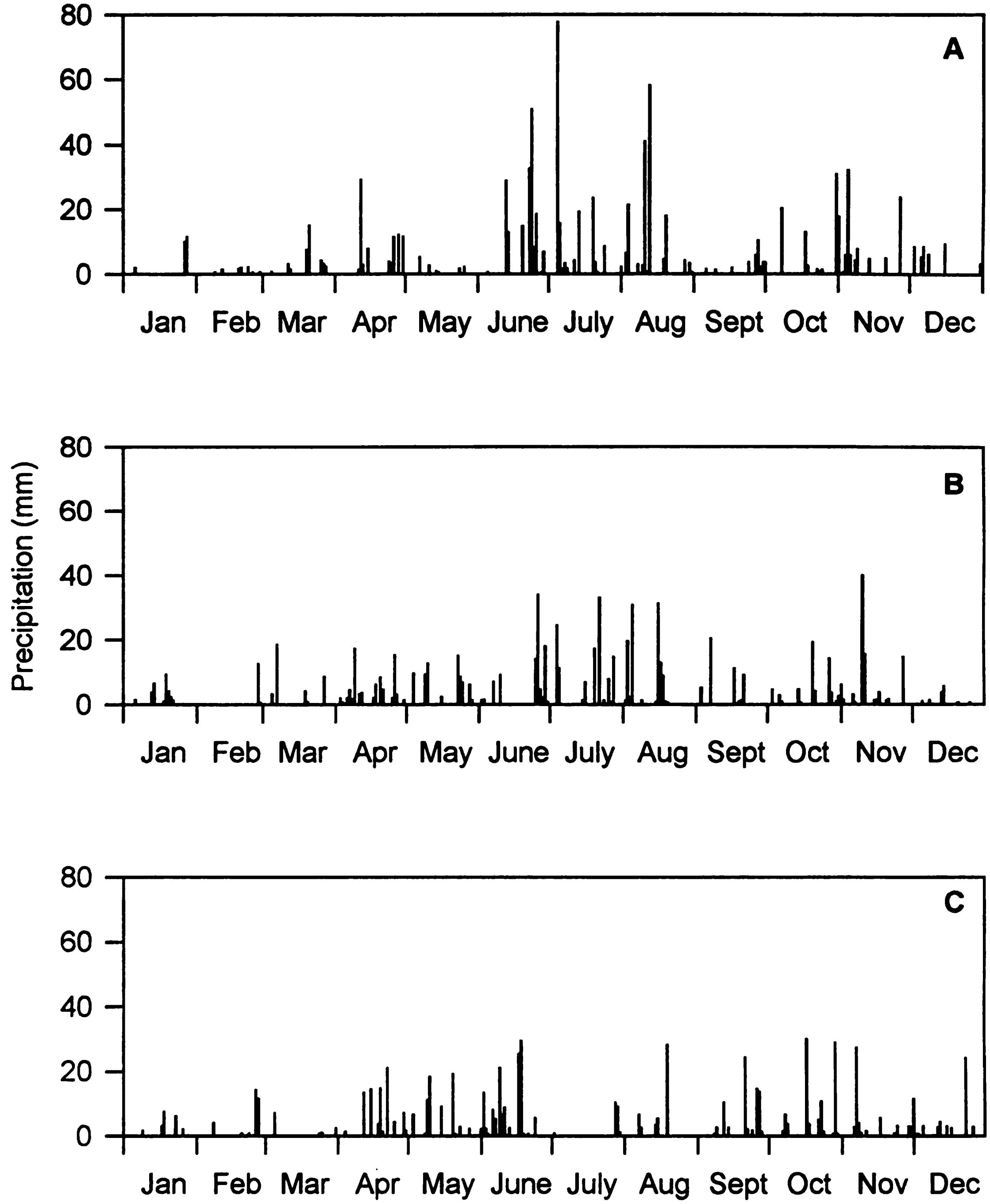


Figure 3.2. Precipitation recorded at the Kellogg Biological Station for 1994 (A), 1995 (B) and 1996 (C).

harvested from the non fertilized plots during the 1995 growing season averaged 253 kg N ha^{-1}.

Total nitrogen contents of whole corn plants were significantly increased by fertilization in 1994 but not in 1996 (Figure 3.3). Tillage did not significantly modify plant nitrogen contents for either CT nor NT treatments of both years. Total N content of whole corn plants in 1996 were 22% lower for fertilized plots and 11% higher for non fertilized plots, over values from 1994. Nitrogen fertilization significantly increased the export of total plant biomass N by 273% and 235% in CT and NT plots, respectively, in 1994 (Figure 3.4). Nitrogen exports by fertilized corn plants from CT plots were 58% higher than from NT plots, in 1994. Tillage did not significantly modify corn N exports in non fertilized plots, in 1994 (Figure 3.4). Neither tillage nor fertilization treatments significantly modified corn N exports in 1996. Exported nitrogen by corn plants in 1996 were 64% and 119% greater than in 1994 for non fertilized CT and NT plots, respectively. The opposite was observed in the fertilized plots, where corn N exports in 1994 from CT and NT plots were 81% and 35% greater than in 1996.

Nitrogen fertilization appeared superfluous for corn production following alfalfa in 1996. Absence of significant increases in corn grain yields by nitrogen fertilization following three years of alfalfa has been previously reported (Fox and Piekielek, 1988). However, our corn yields were particularly poor for the 1996 growing season. Bruulsema and Christie (1987) estimated nitrogen replacement values of alfalfa to a succeeding corn crop to be in the range of 90 to 125 kg N ha^{-1}. All treatments exported less than 100 kg N ha^{-1} in 1996. Consequently, corn

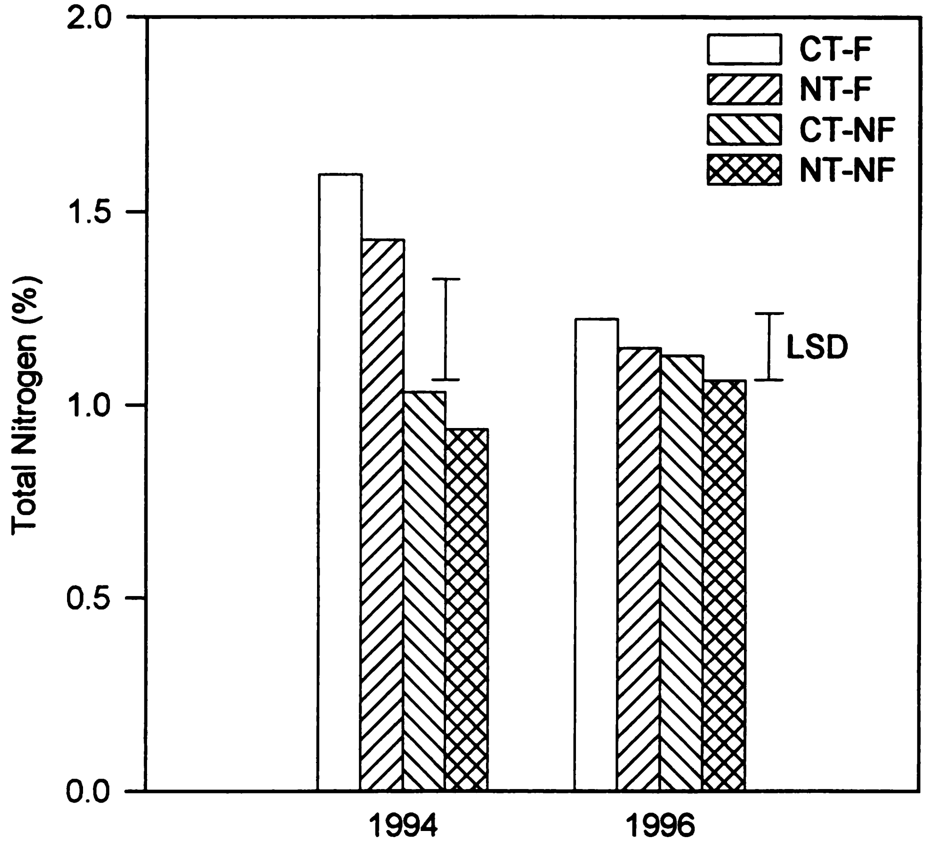


Figure 3.3. Average nitrogen contents of whole corn plants in 1994 and 1996, in conventional tillage (CT) and no tillage (NT) plots, with nitrogen fertilization (F) and with no nitrogen applied (NF).

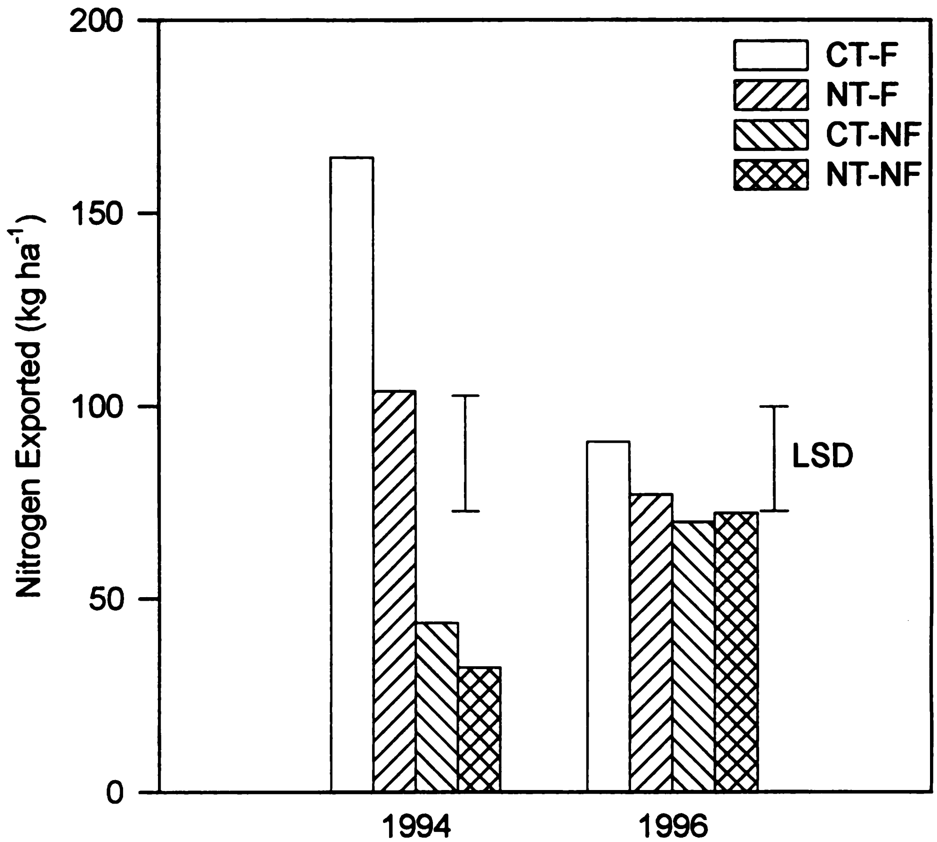


Figure 3.4. Total nitrogen exported by whole corn plants out of conventional tillage (CT) and no tillage (NT) corn plots, with nitrogen fertilization (F) and with no nitrogen applied (NF), in 1994 and 1996.

N requirements following alfalfa might not be completely met during a growing season favorable to maximum corn production.

Soil Soluble Mineral Nitrogen Contents and Leaching

Soluble mineral N concentrations, i.e. NO_3-N + NH_4-N, in the Bt_1 horizon 40 DAP were three times as high in 1996 as in 1994 (Figure 3.5). Nitrogen concentrations peaked in the soil solution about seven weeks after spray-killing the alfalfa in 1996, and were much reduced at 80 DAP of the corn crop. High mineral N levels in the upper part of the soil profile did not induce greater leaching to deeper horizons under CT management in 1996, as maximum concentrations in the Bt_2 and C_1 horizons ranged between 4 and 7 ppm. Mineral nitrogen concentrations in the Bt_2 and C_1 horizons of non fertilized CT lysimeters appeared very similar between 1994 and 1996. Soluble mineral N contents in the Bt_2 horizons of NT lysimeters, 40 DAP of corn, were four times higher in 1996 than in 1994. This suggests that NT lysimeters were subject to higher leaching rates in the upper part of the soil profile than CT lysimeters in 1996. Soluble mineral N levels in the C1 horizon were kept under 6 ppm for CT and NT treatments in 1994 and 1996.

Consistently higher nitrate concentrations were observed in CT than in NT lysimeter leachates, from 22 February 1994 to 28 February 1995 (Figure 3.6A). Similar results indicating higher NO_3-N concentrations in CT vs. NT leachates have been reported by several authors (Randall and Iragavarapu, 1995; Weed

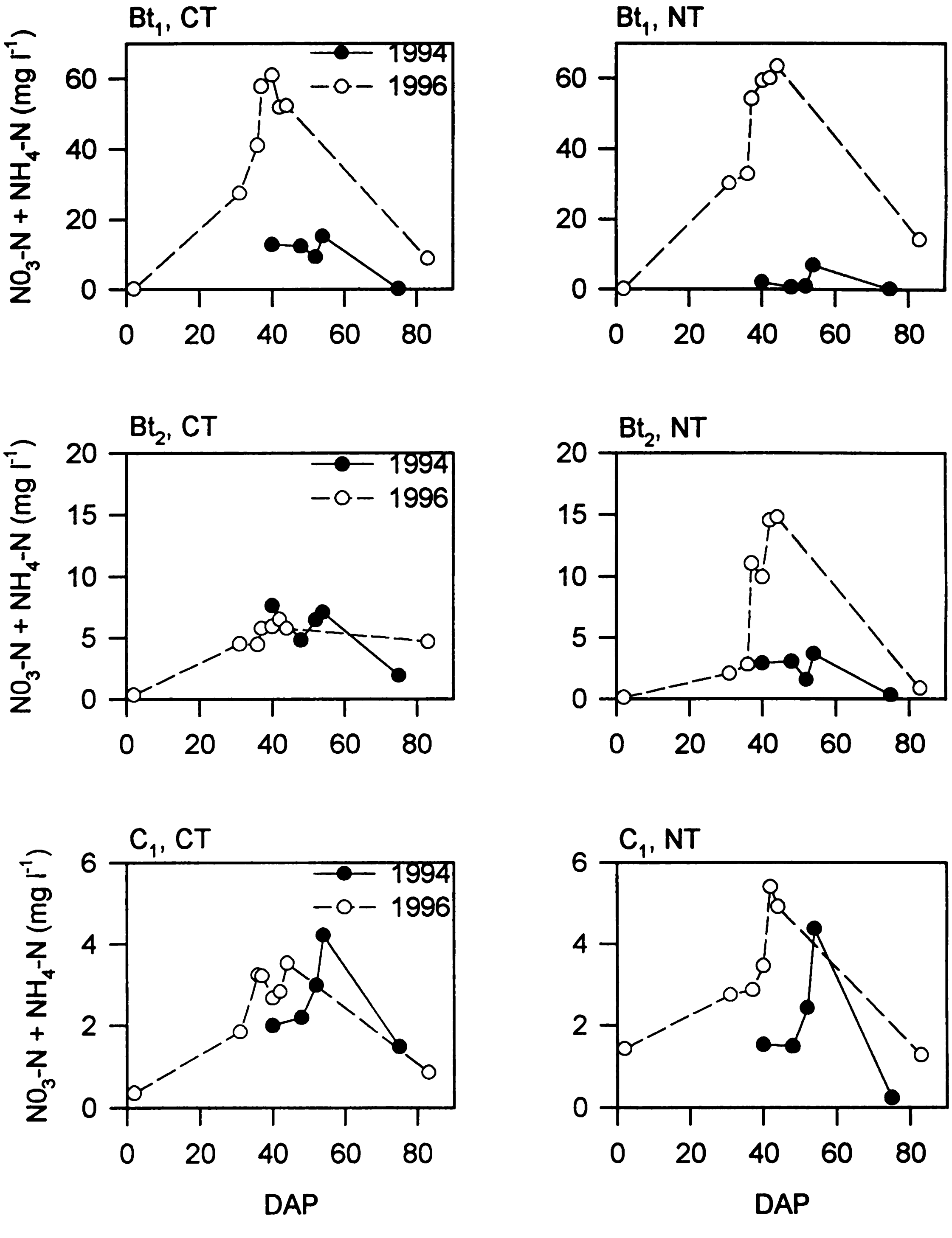
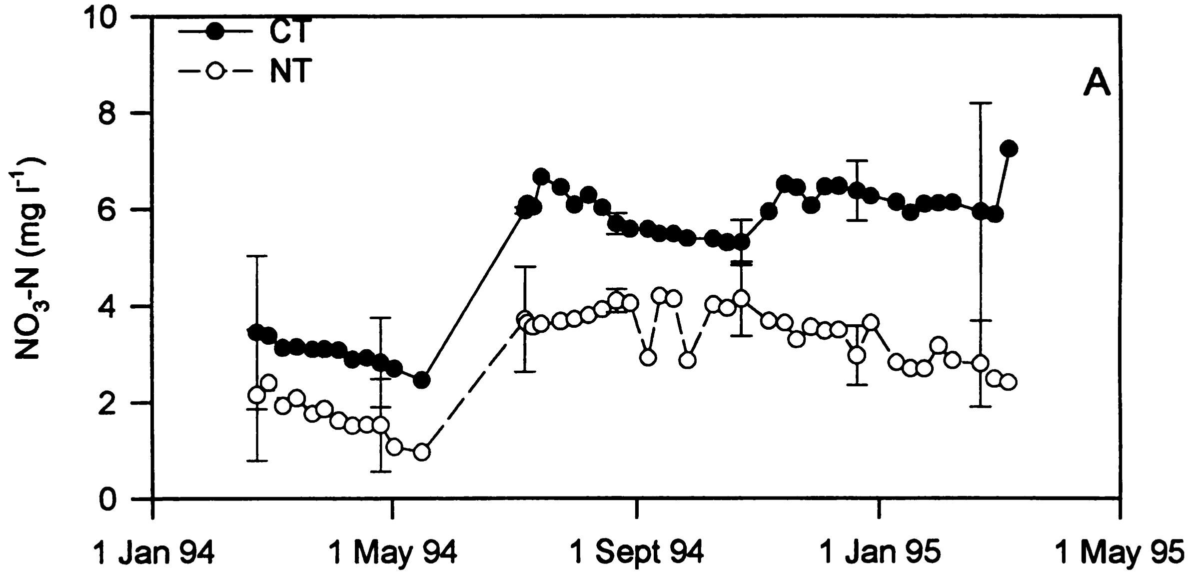


Figure 3.5. Soluble mineral nitrogen from suction lysimeter extractions, in the Bt_1, Bt_2 and C_1 horizons of conventional tillage (CT) and no tillage (NT) monolith lysimeters receiving no N fertilizer, in 1994 and 1996.



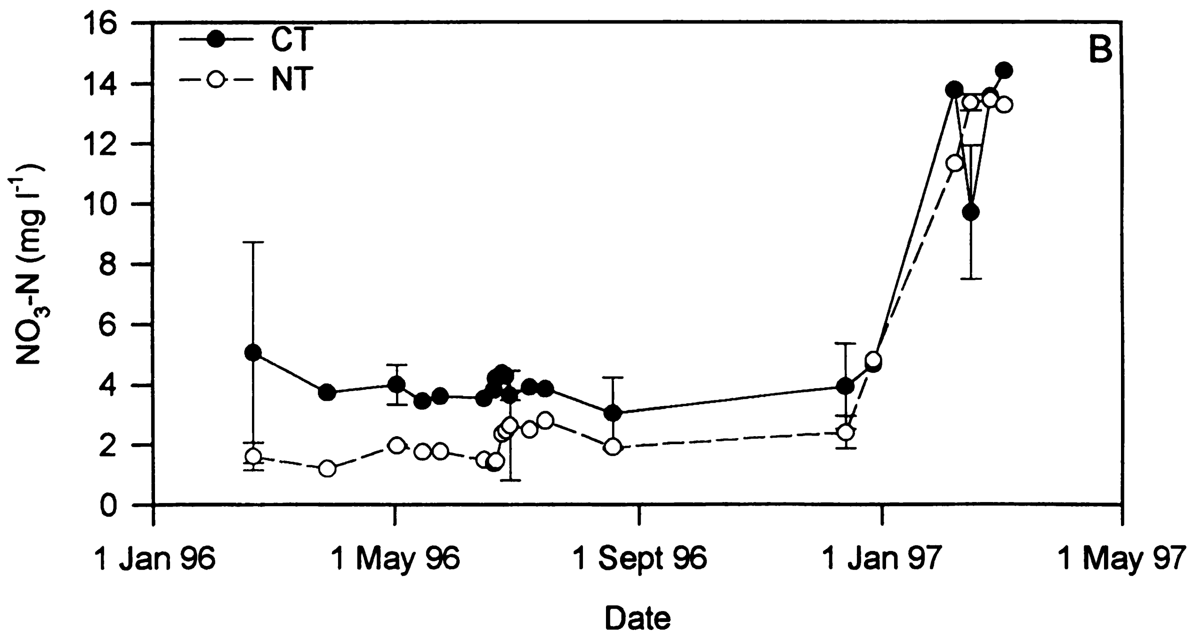


Figure 3.6. Nitrate concentrations of drainage solution from conventional tillage (CT) and no tillage (NT) monolith lysimters from winter 94 to winter 95 (A) and from winter 96 to winter 97 (B).
Standard deviations for two replicates. Reduced number of error bars given for graphical clarity. Error bars might be smaller than symbols.

and Kanwar, 1996). Nitrate concentrations of lysimeter leachates showed little variation from 22 February 1994 to 28 February 1995, except for a small increase during the late spring (Figure 3.6A). Leachate concentrations fluctuated at approximately 4 mg NO_3-N l^{-1} for CT lysimeters and 2 mg NO_3-N l^{-1} for NT lysimeters, throughout 1996. A fairly constant baseline of NO_3-N leaching was observed in 1994, probably corresponding to a equilibrium with previous years of consecutive corn. The slight NO_3-N increase in early summer 1994 suggests a delayed response to spring mineralization burst.

Eighteen months of alfalfa cover progressively reduced NO_3-N leaching to a lower concentration baseline. Only a few data points were available for 1995, yet these do not suggest any peak of NO_3-N leaching under alfalfa (data not reported). Alfalfa mineralization products were not detected in the drainage solution in 1996 (Figure 3.6B), though observed in the Bt_1 and Bt_2 horizons 7 weeks after spray-killing (Figure 3.5). There was an abrupt increase in soil solution NO_3-N from 2-4 to 10-15 mg l^{-1} in early February 1997 (Figure 3.6B). Nitrate concentrations rose to their highest level in three years in February 1997, suggesting that 9 months were necessary for alfalfa-generated NO_3-N to reach soil depths of 2 m. Although considerable fluctuations in NO_3-N concentrations were observed in the Bt horizons (Figure 3.5), leachates at depths of 2 m exhibited only progressive modifications of NO_3-N concentrations (Figure 3.6B).

Cumulative volumes of soil solution drained through NT lysimeters were consistently higher than drainage volumes from CT lysimeters, from 1994 to 1997 (Figure 3.7). These results are consistent with others studies, which

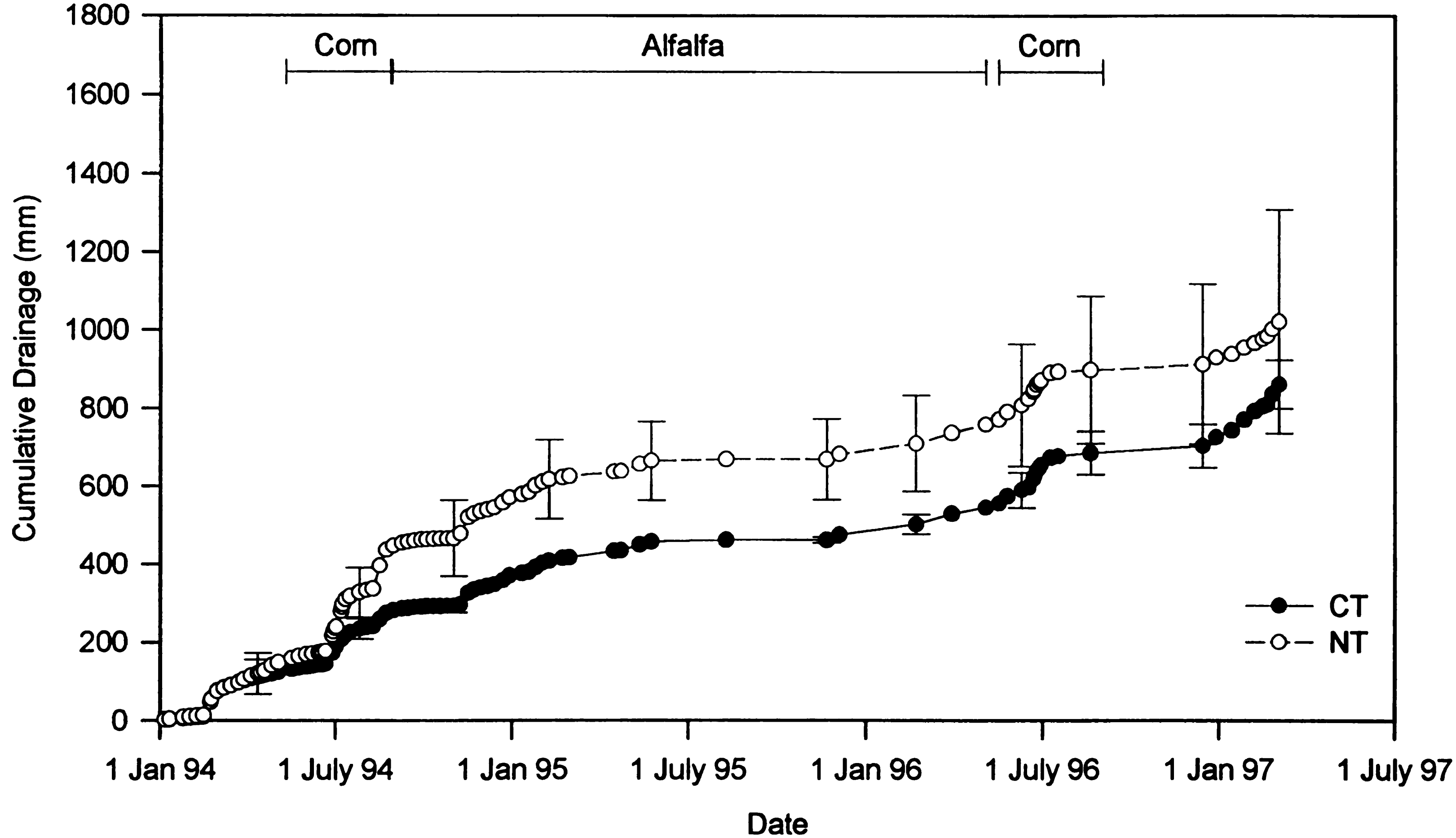


Figure 3.7. Cumulative water drainage out of non-fertilized conventional tillage (CT) and no tillage (NT) lysimeters from February 1994 to March 1997. Standard devitations for n=2. Reduced number of error bars given for graphical clarity. Error bars might be smaller than symbols.

reported higher drainage flows through NT than CT soils (Huang, 1995; Randall and Iragavarapu, 1995; Weed and Kanwar, 1996). Low drainage volumes were observed under alfalfa crop, from Spring 1995 to Spring 1996 (Figure 3.7). Most of the differences in drainage flows between CT and NT lysimeters were observed in 1994, following three years of continuous corn. No apparent tillage-induced modification of drainage flows was observed under or following alfalfa stands (Figure 3.7). Soils remained untilled for 21 months under alfalfa cover, which potentially decreased tillage-induced differences in soil hydraulic properties. Rasse and Smucker (1997) report that, in contrast to corn, the distribution of alfalfa root systems below the Ap horizon is unaffected by tillage treatment. This implies that tillage-induced differences in water flow through soils can potentially be masked by a strong effect of alfalfa root systems on soil hydraulic properties, independent of tillage treatment. Hence, several authors observed increased saturated hydraulic conductivity by alfalfa root -induced macropores (Li and Ghodrati, 1994; Meek et al., 1992; Mitchell et al., 1995). Sufficient decomposition of alfalfa root tissues is necessary to modify saturated hydraulic conductivities of soils (Rasse et al., 1997), which implies that alfalfa root systems can increase drainage flows several months after spray-killing alfalfa stands. Consequently, 21 months of alfalfa cover had the potential for reducing tillage effects on drainage flows, during the alfalfa growth and for several months during root decomposition following the final kill of the stand.

Total amounts of NO_3-N leached from 22 February 1994 to 28 February 1995 averaged 24.8 and 21.0 kg ha^{-1} for non fertilized CT and NT lysimeters respectively (Figure 3.8). The effect of the young alfalfa stand during early growth in the winter can be considered negligible. Baseline leaching levels under corn production on Kalamazoo loam soils approximated 20 kg NO_3-N ha^{-1}, which can be inferred from the non fertilized crops in the large lysimeters. Volumes of soil solution leached under the alfalfa stand were low in 1995 (Figure 3.7). Total NO_3-N leached under alfalfa from 28 February 1995 to 20 February 1996 amounted to 5.6 and 1.9 kg NO_3-N ha^{-1} for CT and NT respectively (Figure 3.8). This confirms the potential of living alfalfa stands to prevent nitrate leaching, as previously reported by several authors (Lamb at al., 1995; Blumenthal and Russelle, 1996). Nitrate leaching were of 24.8 kg NO_3-N ha^{-1} for CT and 15.8 kg NO_3-N ha^{-1} for NT from 20 February 1996 to 04 March 1997, with most of it leached during winter 1997. Consequently, in spite of higher cumulative water drainage and initial carry over of NO_3-N from Ap to Bt horizons, total amounts of NO_3-N lost to deep drainage were lower in NT than in CT lysimeters. Although higher drainage flows are generally reported under NT conditions, total amounts of NO_3-N leached are identical to slightly lower from NT vs. CT plots, due to higher NO_3-N concentrations in CT leachates (Randall and Iragavarapu, 1995; Weed and Kanwar, 1996). Enhanced by-pass flow in NT soils allows soil water to percolate without displacing much of the soil solution in the soil matrix (Singh and Kanwar, 1991). Nevertheless, preferential flow will increase leaching if NO_3-N has not been absorbed by the soil matrix (Tillman and Scotter, 1991). Consequently, preferential flow through recently opened alfalfa root channels, induced by the progressive decomposition of alfalfa root tissue during the few

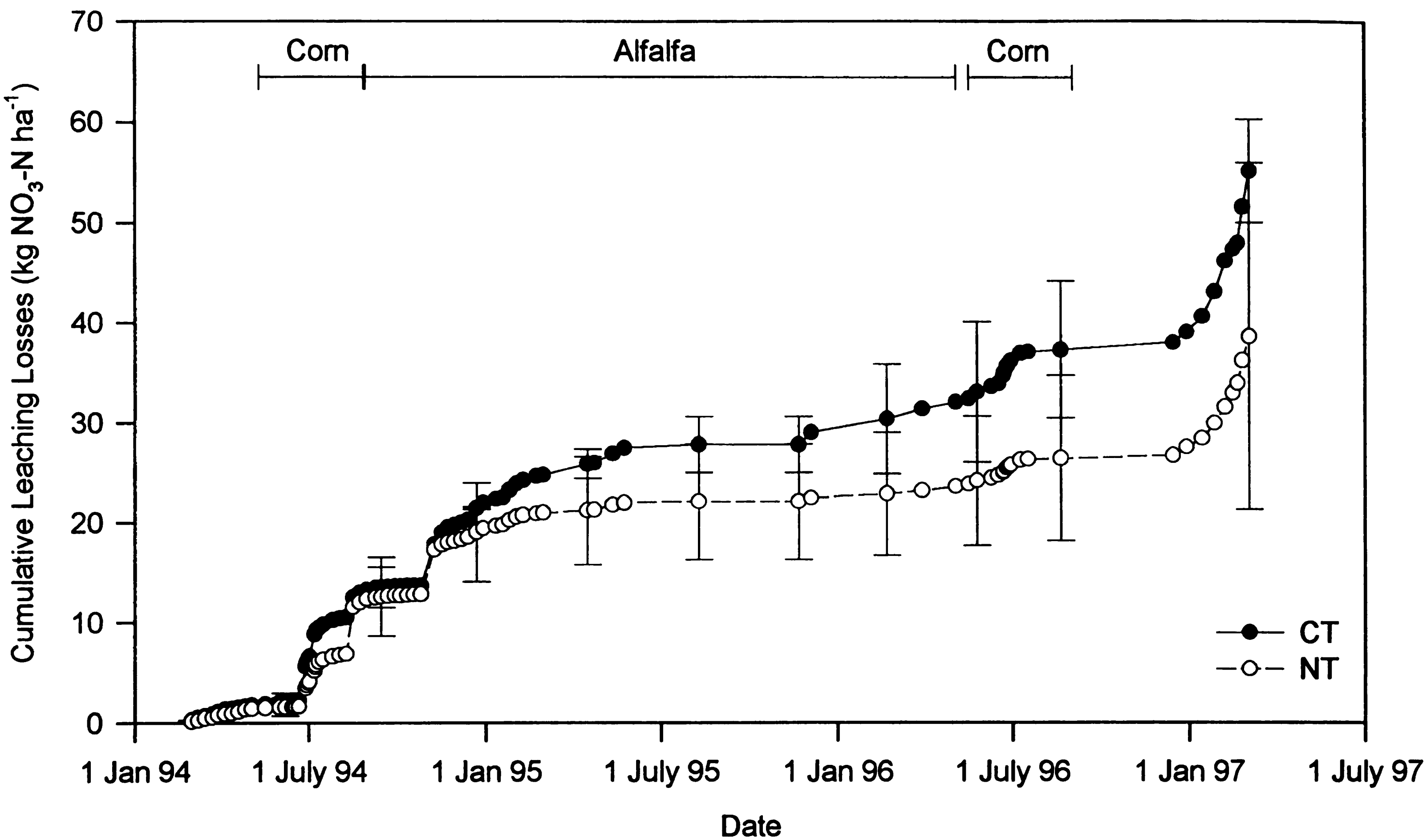


Figure 3.8. Cumulative nitrate leaching losses out of non-fertilized conventional tillage (CT) and no tillage (NT) field lysimeters from February 1994 to March 1997. Standard devitations for n=2. Reduced number of error bars given for graphical clarity. Error bars might be smaller than symbols.

months following spray-killing the alfalfa stand, might have increased NO_3-N leaching from NT compared to CT plots. This hypothesis is supported by higher NO_3-N concentrations in Bt_2 horizons of NT than CT lysimeters 6 weeks after spray-killing the alfalfa stand (Figure 3.5), and by comparable leaching losses from CT and NT lysimeters from August 1996 to March 1997 (Figure 3.8).

Extractable Mineral N in 1996

Extractable mineral N contents of CT and NT soils were low on 03 May 1996, 21 months after alfalfa planting (Table 3.1). No significant differences were observed within horizons for individual treatments or tillage and fertilization factors. The alfalfa crop appeared to have absorbed large quantities of nitrogen throughout the soil profile during the 1995 growing season, rendering differences among treatments insignificant. This confirms previous reports that nitrate leaching under alfalfa stands is minimal (Owens, 1990; Peterson and Russelle, 1991). In contrast, fertilization had a significant effect on soil mineral N contents in the Ap and Bt horizons, on 26 November 1996 (Table 3.2), while little effect was observed for deeper horizons. These data suggest that little N leaching occurred below the Bt_2 horizon or possibly that little N was contained by the C horizons by the end of November 1996. Increases in extractable mineral N between 03 May and 26 November 1996 proved to be 66 and 30 kg N ha^{-1} greater than the amount of N fertilizer applied to CT and NT plots (Table 3.3). Consequently, alfalfa tissue decomposition and soil organic matter mineralization

Table 3.1. Distribution of extractable mineral nitrogen following 21 months of alfalfa within the soil profile of conventional tillage (CT) and no tillage (NT) plots, with nitrogen fertilization (F), and with no nitrogen applied (NF), on 03 May 1996.

	Treatments†				Factors	
	CT-F	NT-F	CT-NF	NT-NF	Fertilizer	Tillage
	kg NO_3-N+ NH_4-N ha^{-1}					
Ap	12.0	9.7	9.9	9.4	NS‡	NS
Bt_1	5.8	6.6	5.5	5.0	NS	NS
Bt_2	4.0	3.2	3.5	3.2	NS	NS
C_1	6.4	6.5	5.6	4.3	NS	NS
C_2	9.1	9.9	8.9	9.9	NS	NS
Total	37.3	35.9	33.4	31.8	NS	NS

† Within horizons, no significant difference by Fisher's $LSD_{0.05}$.
‡ NS = non significant at $P \leq 0.05$.

Table 3.2. Distribution of extractable mineral nitrogen within the soil profile of conventional tillage (CT) and no tillage (NT) plots, with nitrogen fertilization (F), and with no nitrogen applied (NF), on 26 November 1996.

	Treatments				Factors	
	CT-F	NT-F	CT-NF	NT-NF	Fertilizer	Tillage
	—— kg NO_3-N + NH_4-N ha^{-1} ——					
Ap	82.7[a†]	54.8[a]	16.3[b]	12.5[b]	***	NS[‡]
Bt_1	114.3[a]	92.2[ab]	27.8[bc]	11.7[c]	**	NS
Bt_2	14.4[a]	15.7[a]	9.1[a]	6.8[a]	*	NS
C_1	7.8[a]	13.5[a]	10.1[a]	9.8[a]	NS	NS
C_2	7.1[a]	13.1[a]	8.8[a]	10.0[a]	NS	NS
Total	226.3[a]	189.3[a]	72.1[b]	50.7[b]	***	NS

*, **, *** Significant at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, respectively.
† Within horizons, averages indexed with same letter are not significantly different by Fisher's $LSD_{0.05}$.
‡ NS = non significant at $P \leq 0.05$.

Table 3.3. Increases in extractable mineral nitrogen during a corn crop following alfalfa within the soil profile of conventional tillage (CT) and no tillage (NT) plots, with nitrogen fertilization (F), and with no nitrogen applied (NF), between 03 May and 26 November 1996.

	Treatments				Factors	
	CT-F	NT-F	CT-NF	NT-NF	Fertilizer	Tillage
	kg NO_3-N + NH_4-N ha^{-1}					
Ap	70.9[a†]	45.0[a]	6.4[b]	3.1[b]	***	NS[‡]
Bt_1	108.6[a]	85.7[ab]	22.2[bc]	6.7[c]	**	NS
Bt_2	10.4[a]	12.5[a]	5.6[a]	3.6[a]	NS	NS
C_1	1.4[a]	6.9[a]	4.5[a]	5.5[a]	NS	NS
C_2	-2.0[a]	3.2[a]	-0.1[a]	0.1[a]	NS	NS
Total	189.2[a]	153.4[a]	38.6[b]	18.9[b]	***	NS

, * Significant at $P \leq 0.01$, $P \leq 0.001$, respectively.

† Within horizons, averages indexed with same letter are not significantly different by Fisher's $LSD_{0.05}$.

‡ NS = non significant at $P \leq 0.05$.

produced mineral N in excess of corn crop requirements for 1996. Conventional tillage appeared to have induced greater mineral N accumulation than NT in the Ap, Bt_1 and Bt_2 horizons of Kalamazoo loam soils in 1996, though no significant differences could be established for individual horizons (Table 3.3).

Mineralized and applied N accumulated mostly in the Ap and Bt_1 horizons. Extractable mineral N contents in the C_2 horizon changed very little from May to November 1996 (Table 3.3). Soluble and extractable mineral N contents of the C horizons suggest that little nitrate leaching took place from May to November 1996, which is confirmed for non fertilized plots by NO_3-N leaching losses of only 7 kg NO_3-N ha^{-1} for CT and 4 kg NO_3-N ha^{-1} for NT lysimeters during the same period of time (Figure 3.8). Insignificant differences in extractable NO_3-N contents of the C_2 horizon between fertilized and non fertilized plots suggest that there was minimal leaching of NO_3-N even though large quantities (51 - 226 kg ha^{-1}) of mineral N were retained within the profiles (Table 3.2). This may be the result of low rainfall during this period of time.

Assuming negligible leaching and denitrification losses from 03 May to 26 November 1996, total production of mineral nitrogen within the soil profile of CT and NT plots can be inferred from the following formula:

Total N production = gain in soil mineral N + corn N exports - N fertilization

Total mineral N production by the soils for all treatments averaged 115.9 kg N ha^{-1} from 03 May to 26 November 1996 (Table 3.4). This value is comparable to published nitrogen replacement values of 90 to 125 kg N ha^{-1} by alfalfa to a succeeding corn crop as reported by Bruulsema and Christie (1987). Although differences among treatments could not be proven significant, higher mineral N production was observed in CT vs. NT treatments (+47% for F, and +19% for NF). Mineralization rates of alfalfa residues and soil organic matter appear to clearly be modified by tillage management. Angle et al. (1993) report consistently higher soil nitrate concentrations under CT vs. NT corn, whether N fertilizer is applied or not. Alfalfa incorporation to soils might have increased soil organic matter decomposition rates, or basal mineralization. Broadbent and Nakashima (1974) report increased rates of soil organic matter mineralization, called 'priming effect', with plant residue incorporated to soils.

Table 3.4. Estimation of mineralized nitrogen from soil organic matter and alfalfa plant tissues within the 0-150 cm soil profile of conventional tillage (CT) and no tillage (NT) plots, with nitrogen fertilization (F), and with no nitrogen applied (NF), between 03 May and 26 November 1996.

	Treatments				Factors	
	CT-F	NT-F	CT-NF	NT-NF	Fertilizer	Tillage
	——— kg NO_3-N + NH_4-N ha^{-1} ———					
Total	156.8[a]†	107.4[a]	108.4[a]	91.0[a]	NS	NS

† Averages indexed with same letter are not significantly different by Fisher's $LSD_{0.05}$.

CONCLUSIONS

A baseline of NO_3-N leaching in excess of 20 kg ha^{-1} was observed under non fertilized corn, corresponding to NO_3-N concentrations of 6 to 7 mg l^{-1} under CT management. Living alfalfa stand kept nitrate leaching at very low levels. Nitrates levels above EPA recommendation of 10 mg l^{-1} were observed in winter 1997 (Figure 3.6B). These values were obtained in spite of best management practices for corn after alfalfa. Corn was planted directly after spray-killing the alfalfa stand and no nitrogen fertilizer was applied. During a drier year, similar corn yields were obtained whether nitrogen fertilizer was or was not applied, following alfalfa. All nitrogen applied to corn, planted directly after spray-killed alfalfa, was retrieved as soil mineral nitrogen poised for winter and spring leaching, with mineral nitrogen contents of fertilized plots averaging more than 200 kg N ha^{-1} in late November 1996.

Monolith lysimeter and replicated main plot samplings proved complementary in the study of mineral nitrogen dynamics in a corn - alfalfa - corn succession. Lysimeters provided for the non destructive monitoring of temporal mineral nitrogen dynamics within soil horizons and in deep drainage solutions. Replicated main plot destructive measurements at strategic dates provided for mean separation tests among treatments.

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CHAPTER 4

New Root Distribution and Recolonization in a Corn Alfalfa Rotation

ABSTRACT

Distribution of root systems through soils and recolonization of root channels by successive crops are fundamental, though difficult to study, processes of soil ecology. This article reports a minirhizotron study of alfalfa and corn root systems throughout the soil profile of Kalamazoo loam (coarse-loamy, mixed, mesic Typic Hapludalf) monolith lysimeters for a three year succession of corn, alfalfa and corn. Multiple-date comparisons within and between years were conducted to estimate total root densities in each soil horizon. Root recolonization was assessed by comparing every video frame of paired minirhizotrons, from recordings conducted one growing season apart.

Distributions of corn root systems were modified by tillage practices. In 1994, root populations of corn in the Bt_1 horizon peaked 75 to 90 days after planting (DAP). Numbers of corn roots per m^2 in the Bt_1 horizon were consistently higher for NT than CT, in 1994 and 1996. Alfalfa roots showed little response to tillage modifications. However, alfalfa root decomposition rates

responded to different tillage practices and were specific to each soil horizon. Corn root systems growing in soils previously cropped with alfalfa presented similar patterns of root distribution by horizons to root system demographics of the previous alfalfa crop. Successive corn root systems did not display similar distribution patterns throughout the soil profile from one growing season to the next. Proportions of roots of the current crop recolonizing root induced macropores (RIMs) of the previous crop averaged 18% for corn after corn, 22% for alfalfa after corn and 41% for corn after alfalfa, across Bt horizons and tillage treatments.

INTRODUCTION

Distribution of root systems in the soil profile is an important factor in the determination of water and nutrients available to plants (Kuchembuch and Barber, 1987). Root distribution can be considered at the soil horizon scale, i.e. root length density per horizons, or at the root scale, i.e. the diversity of microsites encountered by individual growing roots. Modified distributions of corn (*Zea mays* L.) root systems within the soil profile have been observed under contrasting fertilizer rates (Anderson, 1987; Durieux et al., 1994), irrigation (Robertson, 1980), and tillage management studies (Anderson, 1987; Bauder et al., 1985; Vepraskas and Wagger, 1990). Development of the corn root system is facilitated at depths where optimal conditions for water, nutrients and soil physical properties are met. Much less understood is the response of corn root systems to root-induced macropores (RIMs) and associated decomposed root tissues from previous crops which present heterogenous options for root distribution.

The specific recolonization of RIMs by developing root systems of current crops has been suggested as an important factor influencing root growth and water movement through soils (Smucker et al., 1995). Root colonization of horizons has been reported to be in direct relationship with the number of soil biopores (Wang et al., 1986). Alfalfa (*Medicago sativa* L.) in rotation with corn has been reported to promote corn root distribution in the soil profile by creating accessible RIMs for corn root development (Stone et al., 1987). This mechanism certainly bears trophic implications. Plants restitute substantial amounts of carbon and nitrogen to soils through root exudation and decay (Milchunas et al., 1985; Smucker, 1984). The colonization of recent RIMs and root growth along decaying root tissue can play an important role for plant nutrition in both rotation and intercropping systems (Smucker, 1993). Carbon inputs from alfalfa root systems to soils were assessed to be five times higher than corn root contributions (Angers, 1992). During the growing season significant amounts of atmospheric fixed nitrogen can be transferred from alfalfa to intercropped plants (Brophy et al., 1987; Ta and Faris, 1987). Consequently, root proximity to nutrient source, i.e. decaying root tissue, can play an important role in plant nutrition.

Minirhizotron (MR) techniques have been widely used to characterize the distribution of root systems within soil profiles. This non-destructive approach is a unique opportunity for multiple sampling throughout the growing season, and provides comparative images of roots which can be utilized for determining root turnover (Smucker, 1990). Variation of total root numbers across time have been used to assess root death, turnover, and new root production for given soil depth increments or horizons (Huang, 1995; Pietola and Smucker, 1995). Specific root turnover can also be assessed by monitoring the temporal succession of root growth in every single recorded video frame along the MR tube (Cheng at al., 1990 and 1991). This second technique is more precise but more time consuming. Temporal analyses of root development and decay in individual MR frames have also been used to assess root colonization of RIMs and lines of least resistance (Rasse and Smucker, 1995). Year to year comparison of root dynamics in individual MR frames is limited to MR tubes that can be kept in place for multiple years. Field-installed MR tubes have generally been removed for harvest and tillage operations. Horizontal MR tubes, installed in the wall of monolith lysimeters or access tunnels into the field are appropriate for multiple-year studies (Lizazo and Ritchie, 1997; Goins and Russelle, 1996; Rasse and Smucker, 1995).

This article reports the development of alfalfa and corn root systems throughout the soil profile of Kalamazoo loam (fine-loamy, mixed, mesic Typic Hapludalf) monolith lysimeters for a three-year succession of corn, alfalfa and corn. Distributions of root systems per horizons are compared for conventional (CT) and no tillage (NT) systems. Root recolonization of RIMs and decaying roots is assessed for corn after corn, alfalfa after corn, and corn after alfalfa, by visually comparing individual video-recorded MR frames over time.

MATERIAL AND METHODS

Experimental Design and Treatments

Four monolith lysimeters were installed in a long-term field experiment on a Kalamazoo loam soil at the Kellogg Biological Station in southwestern Michigan. Soil horizons are a loamy Ap from 0 - 0.25 m which overlays a clay loam Bt_1 from approximately 0.25 to 0.55 m, which overlays a Bt_2 horizon enriched in coarse material from 0.55 to 0.80 m, which is underlain by a coarse glacial outwash parent material. The lysimeters, 1.2 x 1.8 m of surface area and 2.1 m deep, installed in duplicate in 1990, are part of a replicated field experiment established in 1986 to investigate N supply and tillage effects on soil-plant interactions (Aiken, 1992). Conventional tillage plots were moldboard plowed in the field, and the lysimeters were manually spaded in the second week of April 1994. No tillage (NT) lysimeters were non-disturbed. Roundup was applied at rate of 7 l ha^{-1} 03 May 1994. Corn (Pioneer hybrid 3573) was planted at 67,700 seeds per hectare in all plots and manually planted in lysimeters on 6 May 1994. The rows of corn were planted at high density in the lysimeters and later thinned to guarantee a uniform plant density matching field conditions. The corn canopy was continuous across the lysimeter to field interface, with the exception of a 1 m gap over each access chamber adjoining each lysimeter. Corn harvest was conducted on 23 August 1994. Moldboard plowing, followed by a light discing was performed on all CT plots on 29 August 1994. Lysimeters under CT treatment were manually spaded to 20 cm. Roundup was sprayed on all NT plots and lysimeters at rate of 7 liters per hectare on 30 August 1994. Alfalfa (Pioneer 5246) was sown in all plots on 1 September 1994. All plots received 112 kg K_2O ha^{-1} and 337 kg ha-1 of pellet lime on 7 April 1995. Alfalfa was harvested on 12 June, 22 July and 1 September 1995. Alfalfa was spray-killed on 02 May 1996 with Roundup at 4.6 l ha^{-1} and 2-4D ester at 2.3 l ha^{-1}. Conventional tillage plots were moldboard plowed and disced on 8 May 1996. Corn (Pioneer hybrid 3573) was drilled in all plots at rate of 67,700 seeds per hectare on 13 May 1996. Corn was harvested as ensilage on 4 September 1996.

Instrumentation and Measurements

Each lysimeter is equipped with a steel access chamber, which is positioned directly along the lysimeter and gives access to one full side of the monolith. Access ports for instrumentation were cut in the stainless stell wall separating the monolith from the access chamber. Horizontal polybutyrate minirhizotron (MR) tubes were installed in the Bt_1, Bt_2 and top C horizons of each lysimeter, directly under the central corn row. No MR tube could be installed in the Ap horizon due to tillage constraints. Though no data were collected in the Ap horizon, other rhizotron studies have shown that corn root systems present highest densities from 30 to 50 cm depth (Tan and Fulton, 1985), or in the Bt_1 and Bt_2 horizon of Kalamazoo loam soils (Huang, 1995). Root intersections with the upper surface of MR tubes were recorded with a minirhizotron color microvideo camera (Bartz Technology, Santa Barbara, CA) equipped with an index handle (Ferguson and Smucker, 1989). Identical frame positions, 1.35 x 1.8 cm each, were recorded in 1994-1996. Two previous recordings in November 1992 and August 1993 were also available for the study. Permanently installed MR tubes presented a background of roots at different stages of decomposition from previous growing seasons. Initial analyses of the May 1994 pictures proved that large amounts of corn roots from the previous growing season showed little or no sign of decomposition, and could not be discriminated from newly developing roots. Consequently, new roots of the current crop were counted against the background of roots from the previous crop. Simultaneous observations of two video recordings were conducted on two VCR-monitor sets by comparing each frame to a reference date, free of new roots. High quality 4 heads VCR and 6 heads VCR were used for flawless paused images, necessary to precisely identify and count specific roots at specific locations. Root development observations were conducted on all MR tubes located 1 cm below and 6 cm above the upper regions of each soil horizon. Root recolonization evaluations were performed on one MR tube in each Bt_1 and Bt_2 horizons for each lysimeter. The C horizon was not analyzed for root recolonization as no roots were observed for NT corn down to the C horizon in 1994. Corn root systems at their maximum development, i.e. in early August 1994 and 1996, were compared to root systems of the previous crop at their stage of maximum development, i.e., in early August 1993 for corn, and just before spray-killing alfalfa on 02 May 1996. Alfalfa root systems in June 1996 were compared to corn root systems in August 1995. June was chosen for visual evaluating alfalfa root recolonization so that sufficient root extension throughout the Bt horizons was completed without significant root recolonization of alfalfa by itself following root turnover. A new root was considered to recolonize an old root, decaying or residual channel (RIM), when the new root grew tangentially, at distances $\leq$ 0.5 mm, to the old root location for at least 20% of the length of the new root. A new root which grew within the above parameters, and may have occupied more than one old RIM, qualified as one reoccupation only. Old root channels were only considered valid if they had been clearly invaded or occupied by a root during the previous growing season (Figure 4.1). Root channels vacant for more than one year, before root occupation, were not considered to be recolonized. Information for each MR frame consisted of: 1) total root number for the previous growing season, 2) total number of new roots, 3) number of new roots recolonizing decomposing old roots or their associated RIMs of the previous year, 4) number of new roots that were not recolonizing old roots or RIMs of the previous year. These numbers were then calculated and presented in percentage of new roots recolonizing old roots.

Soil water contents were estimated by time domain reflectometry (TDR). Probes, inserted at same depths as MR tubes, were composed of two metal rods, 30.5 cm long and 0.5 cm in diameter, installed horizontally 5 cm apart in the soil profile. Soil moisture data were collected with a TDR-meter model 1502C (Tektronix Inc, Beaverton, Oregon, U.S.A.). Transformation of TDR readings into

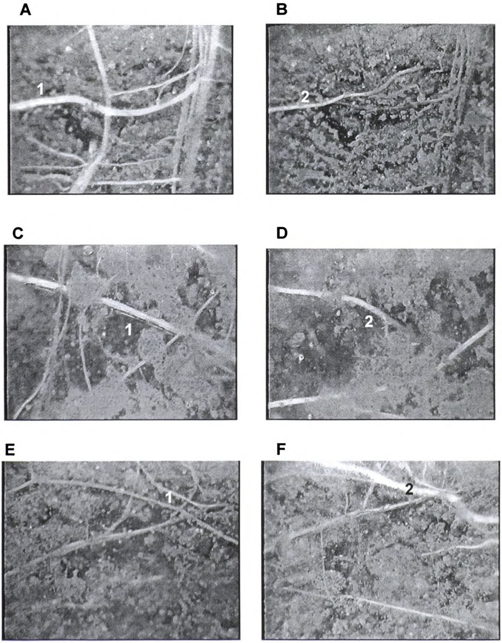

Figure 4.1. Minirhizotron pictures of corn roots in 1993 (A), corn roots in 1994 (C) and alfalfa roots in 1995 (E), shown decayed at the next growing season and recolonized by corn (B), alfalfa (D) and corn roots (F). 1 future recolonized root, 2 new recolonizing root

volumetric water contents was performed using Topp's equation (Topp et al., 1980).

Statistical Analyses

A year to year comparison of individual MR tubes in corn alfalfa rotation was possible because of the horizontal insertions of the MR tubes in monolith lysimeters. The weakness of the design resides in the low replication level due to the very high cost of lysimeter installation. Error bars were represented by standard deviations, as standard errors of duplicated samples can be misleading with respect to the significance of mean separation. Averages of two replicates were compared by F-test (SAS institute, 1989) between horizon for similar tillage and year, and between tillage for similar horizon and year.

RESULTS AND DISCUSSIONS

Corn roots reached the Bt_1 horizon about 35 days after planting (DAP) in 1994 (Figure 4.2). Root population of corn in 1994 peaked 75 to 90 DAP in the Bt_1 horizon (Figure 4.2). Maximum length of the corn root system has been reported to occur around 80 DAP (Barber, 1986; Huang, 1995), remain relatively constant for two weeks and then decline rapidly (Mengel and Barber, 1974). Consequently, maximum root development in the Bt_1 horizon of Kalamazoo loam soils for this multiple-year study appeared concomitant with maximum corn root length throughout the entire profile. This minirhizotron study presented an

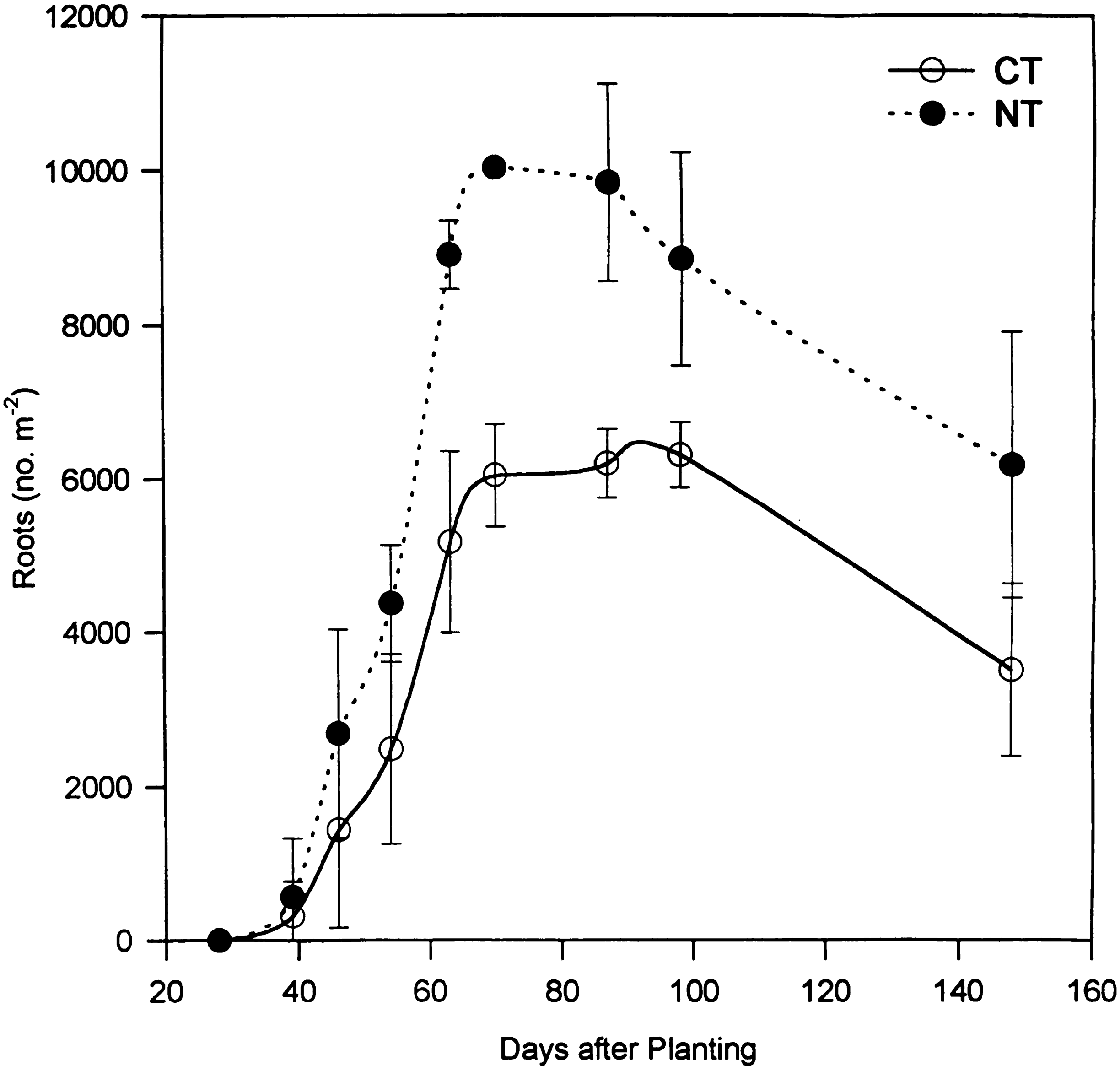

Figure 4.2. Corn root demographics in the Bt_1 horizon of convetional tillage (CT) and no tillage (NT) lysimeters in 1994. Standard deviations for n = 2 represented.

identical time sequence for corn root development as was previously reported by destructive root extraction studies (Barber, 1986; Mengel and Barber, 1974). Corn roots reached the Bt_2 horizon about 55 DAP (Figure 4.3). Numbers of corn roots per m^2 in the Bt_1 horizon were consistently greater for NT than CT, in 1994 and 1996 (Figure 4.3). This increased corn root population under NT in the Bt_1 horizon was statistically significant ($P \leq 0.05$) in summer 1994, despite the limitation of having only duplicated samples. Tillage modifications of corn root populations in the Bt_2 horizon were different in 1994 and 1996. Conventional tillage management tended to favor corn root colonization into the Bt_2 horizon in 1994 (Figure 4.3). Corn roots reached the C horizon about 75 DAP in the CT lysimeters in 1994, while no corn root was observed in the C horizon of NT lysimeters (Figure 4.3). Both treatments showed corn roots down to the C horizon by August of 1996, though CT accumulated greater amount of roots. Considering the overall corn root profile in 1994 and 1996, NT favored higher root densities in the upper part of the soil profile, while CT induced root growth in deeper horizons. Several studies have reported a preferential accumulation of corn roots in the top Ap horizon of NT versus CT soils (Anderson, 1987; Bauder et al., 1985; Newell and Wilhelm, 1987) . Huang (1995) observed increased corn root density in the Ap horizon of Kalamazoo loam soils for NT versus CT. She also reported in the C horizon root densities decreased for NT versus CT one year out of two. Alfalfa root growth in 1995 and early spring 1996 was not consistently modified by tillage (Figure 4.3). Alfalfa root populations peaked in May 1996, just before the spray-killing of the crop. This burst in alfalfa fine root

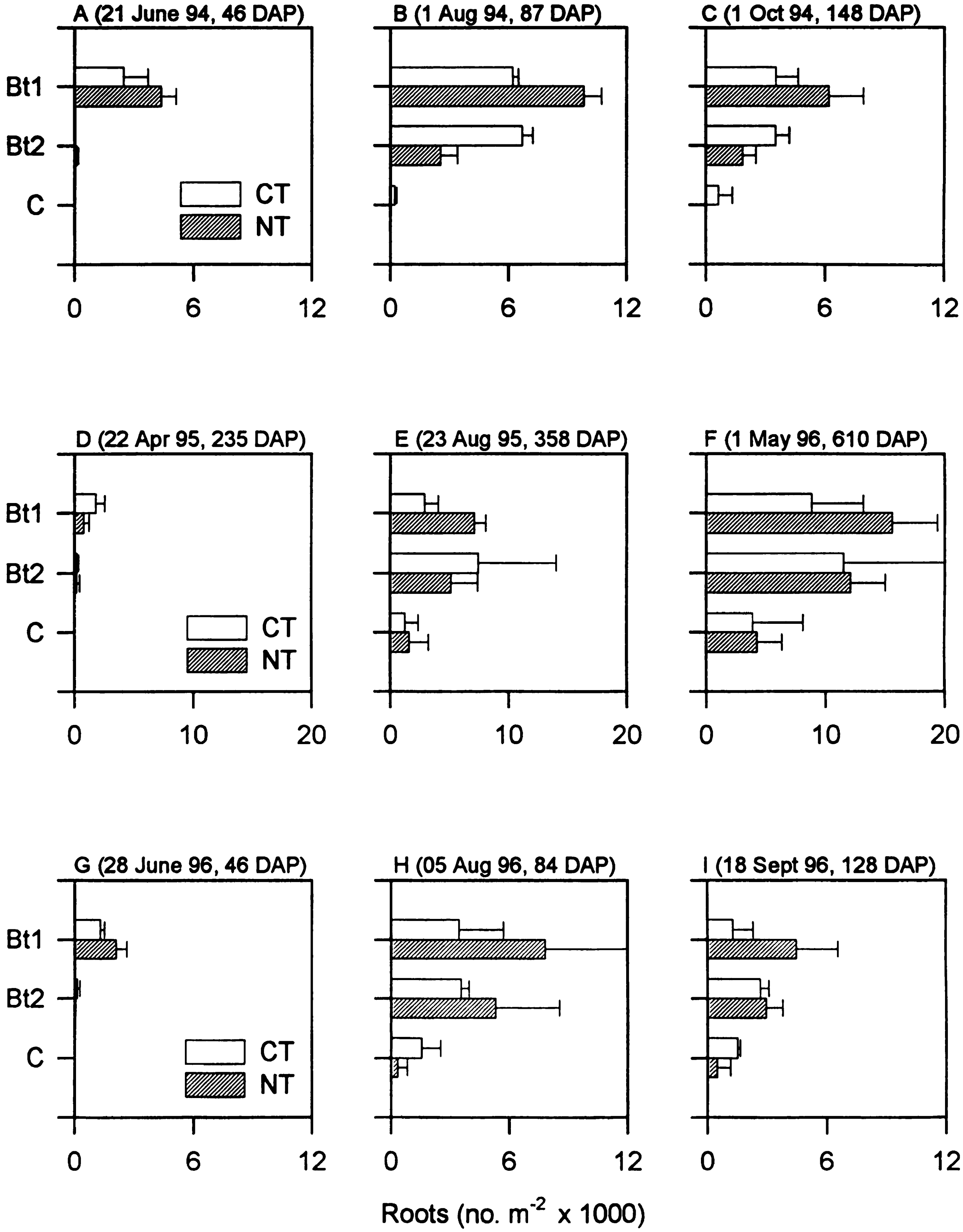

Figure 4.3. Root demographics per horizons in conventional tillage (CT) and no tillage (NT) lysimeters for corn 1994 (A,B,C), alfalfa 1995 & 1996 (D, E, F), and corn 1996 (G,H,I). Standard deviations for n =2 represented.

development in early spring has been reported by several authors (Jones, 1943; Pietola and Smucker, 1995; Rechel et al., 1990).

For the 1993 to 1996 growing seasons, maximum development of corn roots in August in the top Bt_1 horizon were compared to lowest soil water contents reached before 1 July in the identical soil layer (Figure 4.4). A significant correlation ($r^2 = 0.92$) was observed between roots and minimum soil water contents for corn in 1994. The two NT lysimeters presented greater soil water contents in the Bt1 horizon than the two CT lysimeters in 1994 (Figure 4.4). In 1995 for alfalfa and 1996 for corn, correlations between total roots and minimum soil water contents were non significant (n=4), however a positive trend between these two variables was observed. Combined data for corn in 1994 and 1996 presented a pronounced ($r^2 = 0.88$) correlation between total roots and minimum soil water contents. This correlation suggests that corn root populations in the Bt_1 horizon of Kalamazoo loam soils negatively responded to soil water deficits experienced earlier in the growing season. These findings concur with studies reporting that irrigated corn developed greater root populations in the upper part of the soil profile than non irrigated corn (Newell and Wilhelm, 1987; Robertson et al., 1980), while non irrigated corn presented similar to higher root populations at depth greater than 30 cm. Maximum root populations were not significantly correlated to minimum soil water contents reached before July first in the Bt_2 and C_1 horizons. This absence of positive correlation probably resulted from the low amplitute of soil water content variations for the Bt_2 and C_1 horizons.

Root distributions within the soil profiles, represented by the total root

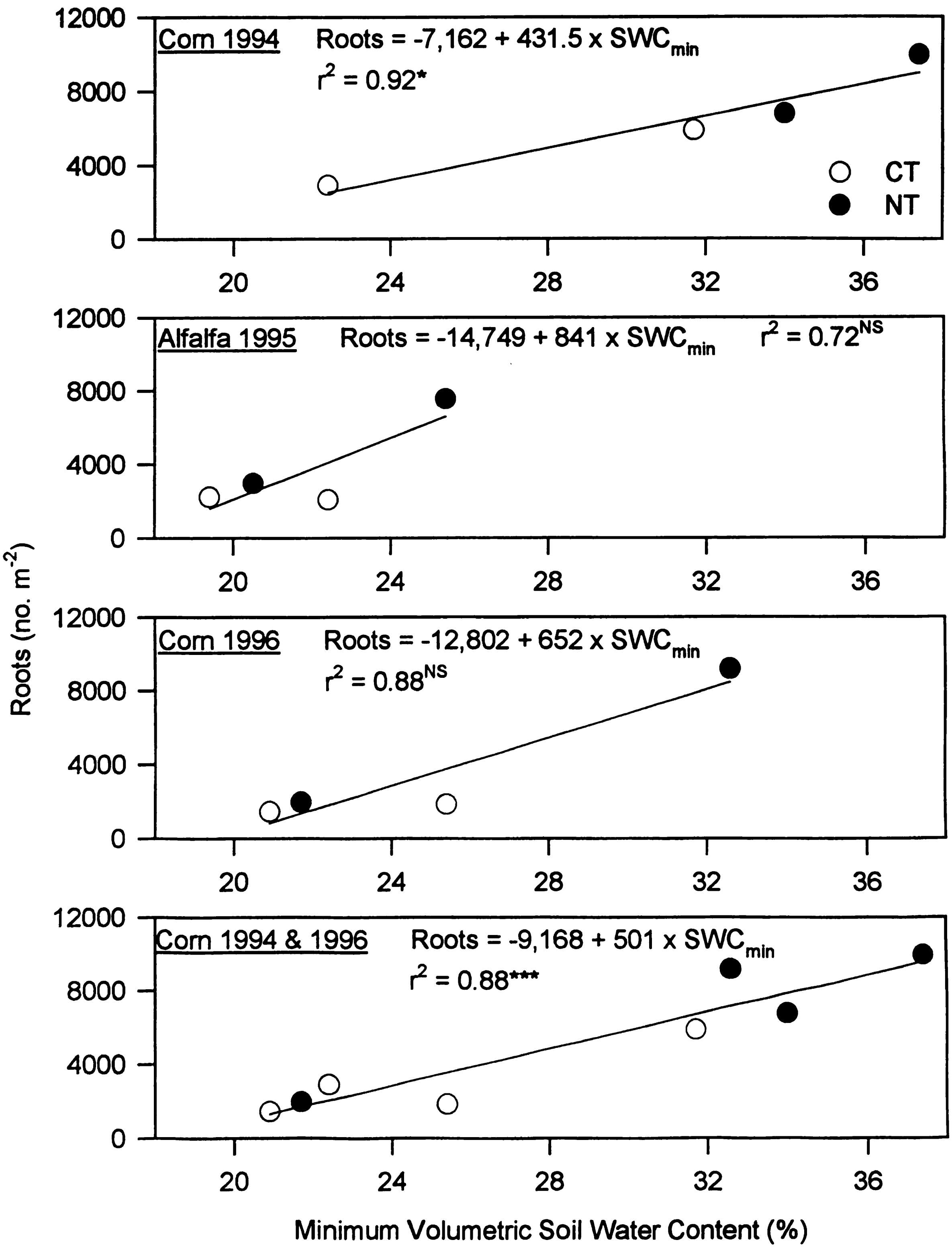

Figure 4.4. Correlation between minimum volumetric soil water contents (SWC_{min}) reached before 1 July and root numbers observed in August of the same year, in the top Bt_1 horizon of conventional tillage (CT) and no tillage (NT) lysimeters.

numbers for each individual MR tube, were compared for the 1993 to 1996 growing seasons (Table 4.1). Distribution of corn root systems (1996) proved significantly correlated to the distribution of the previous alfalfa root systems (1995). The distribution of corn root systems (1994) showed virtually no correlation with the one of the previous corn crop (1993). The colonization of soil horizons by alfalfa root systems (1995) were not significantly correlated to the distribution of previous corn roots (1994). These results suggest that the development of corn root systems within the soil profile was positively affected by the distribution of the previous alfalfa crop.

Table 4.1. Correlations of total root numbers per minirhizotron tubes across tillage treatments and horizons, among four consecutive growing seasons from 1993 to 1996.

	Aug 93 (corn)	Aug 94 (corn)	June 95 (alfalfa)	Aug 96 (corn)
Aug 93 (corn)	1	-0.01	0.51	0.43
Aug 94 (corn)		1	0.11	0.21
June 95 (alfalfa)			1	0.84**
Aug 96 (corn)				1

** Significant at $P \leq 0.01$.

Root recolonization of decomposing roots or RIMs, analyzed within the individual MR frames, showed different patterns for the three years of study (Table 4.2). Root recolonization averaged 18% for corn after corn (1994), 22%

Table 4.2. Proportion of new roots recolonizing decomposed roots from the previous growing season, for 1994 (corn after corn), 1995 (alfalfa after corn), and 1996 (corn after alfalfa).

Tillage	Horizon	1994	1995	1996
		%		
CT	Bt_1	9.3 (4.1)†	15.5 (0.7)	45.0 (10.1)
	Bt_2	16.5 (6.8)	30.5 (13.4)	37.8 (2.6)
NT	Bt_1	16.4 (12.7)	21.4 (2.6)	35.6 (4.5)
	Bt_2	29.6 (7.8)	22.0 (9.0)	43.8 (1.3)

† Standard deviations for two replicates.

for alfalfa after corn (1995) and 41% for corn after alfalfa (1996), across the two horizons and two tillage treatments. The proportion of new roots recolonizing RIMs and decomposing roots appeared to be unaffected by tillage and soil horizon. Individual MR frames can intercept linearly growing corn roots on a maximum length of 2.25 cm, corresponding to the diagonal of each video frame. Consequently, every 2.25 cm segment of corn root had a probability greater than 40% to be partially recolonizing the RIMs and decomposing roots established by a previous alfalfa crop. Corn root recolonization in 1996 of decaying root channels or RIMs of the previous alfalfa crop (1995) were 2.7-fold greater than corn root recolonization in 1994 of decaying root channels and RIMs of a previous corn crop (1993). Although seasonal affects on root growth may have influenced the magnitude of the results somewhat, seasonal by previous crop affects can only be separated by future studies involving simultaneous factorial experiments. These results also assume that root recolonizations at the surfaces of MR tubes are identical to recolonization in the bulk soil. Although this study does not prove that the MR tube surface could enhance or discourage root recolonization, there is no reason to think that different crop root systems would behave differently towards root recolonization at MR surfaces compared to the bulk soil. Consequently, it appears that corn roots recolonized RIMs and decomposing roots of alfalfa to much greater extent than did corn roots following corn.

The percentage of new roots involved in recolonization, across tillage treatments and horizons, was significantly correlated to root populations of the year before, for corn (1994) after corn (1993) and alfalfa (1995) after corn (1994) (Table 4.3). This positive correlation was expected, as greater number of roots from the previous growing season generated greater number of RIMs available to recolonization by new roots of the current crop. However, no significant correlation was observed between alfalfa root populations in 1995 and proportion of corn roots recolonizing alfalfa RIMs in 1996 (Table 4.3).

Table 4.3. Correlations between the proportion of new root recolonization, i.e. number of new roots recolonizing RIMs divided by the total numbers of new roots, and the number of old roots from the previous growing season. Correlations conducted for n = 8, across 2 horizons and 2 tillages for 2 replicated lysimeters.

Number of old roots	Proportion of new root recolonization		
	1994 (corn)	1995 (alfalfa)	1996 (corn)
Nov 93 (corn)	0.83*		
Aug 94 (corn)		0.75*	
Aug 95 (alfalfa)			0.26

* Significant at $P \leq 0.05$.

These results suggest that corn root recolonization of alfalfa RIMs did not only depend on total RIM numbers but were also affected by selective RIM properties. Alfalfa root ages varied from a couple of days to more than a year old, and therefore different root decomposition activities were present when the alfalfa crop was spray-killed. Corn was planted immediately afterwards. Corn roots might have recolonized only certain types of alfalfa roots having reached a certain decomposition stage. The distribution of alfalfa root age classes and decomposition properties might have been modified by tillage and horizons (Figure 4.3), therefore leading to recolonization percentages only partially dependant upon old and new root populations. To support this hypothesis, alfalfa root decomposition rates were estimated from 1 May to 5 August 1996 (Figure 4.5). Alfalfa root populations on 5 August 1995 were estimated by counting total root numbers and subtracting corn root populations, the difference consisting of apparently undecayed alfalfa roots. Between 70 and 84% of alfalfa roots appeared to be decomposed on MR frames three months after spray-killing the crop. Alfalfa roots in the Bt_1 horizon were significantly more decomposed in CT than in NT lysimeters, while the opposite was true in the Bt_2 horizon (Figure 4.5). Differential decomposition rates of alfalfa roots were induced by tillage, which supports the hypothesis that factors other than root and RIMs populations might be involved in determining root recolonization rates. Other factors, such as alfalfa RIM size distributions might have affected corn root recolonization. While Stone et al. (1987) reported that alfalfa RIMs favor corn root penetration into soils, it has also been observed that large biopores (> 1 mm) can be detrimental to plant growth (Passioura and Stirzaker, 1993), and that few corn roots would develop in biopores of dimensions greater than their own radius (Logston and Allmaras, 1991). The results of this study indicate that corn root recolonization of alfalfa RIMs can potentially be modified by the extend of the period between spray-killing the alfalfa stand and corn plantation.

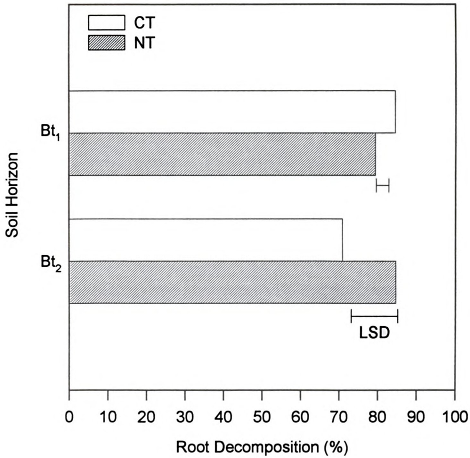

Figure 4.5. Alfalfa root decomposition from 1 May to 5 August 1996, in Bt_1 and Bt_2 horizons of conventional tillage (CT) and no tillage (NT) monolith lysimeters.

CONCLUSIONS

Distributions of corn root systems were modified by tillage practices, while alfalfa roots showed little responses to tillage modifications. No-tillage promoted higher corn root densities in the upper part of the soil profile compared to conventional tillage. Modified alfalfa root decomposition rates resulted from different tillage practices, and were specific to each horizon. In conclusion, tillage effects on roots were not limited to the plowed layer, and affected different aspects of root ecology such as root density and decomposition rate.

Root recolonization of successive crops is a very difficult mechanism to study. Though research has been limited on the subject, a better understanding of this processus would shed new light on many issues of soil ecology. Root recolonization of successive crops potentially influences: 1) access of root systems to different part of the soil profile, 2) plant absorption of mineralization products from decaying root tissue, 3) root contacts with pathogenetic microbial communities, 4) movement of water through soils, and 5) nitrate leaching. Corn root systems growing in soils previously cropped with alfalfa presented similar patterns of root distribution by horizons to previous alfalfa root systems. Consecutive corn root systems did not display consistent distribution throughout the soil profile from one year to the next. Corn roots developing in a previously cropped alfalfa field recolonized alfalfa RIMs and decomposing roots at more than 40%. This mechanism can facilitate corn root penetration through compacted horizons by following alfalfa RIMs. Nutrient acquisition by corn roots is potentially facilitated by the direct contact between growing roots and decomposing legume tissues. The plugging effect of empty corn root channels by alfalfa roots can potentially reduce water flow and leaching through soils.

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SUMMARY AND CONCLUSIONS

This research advocates the need for a greater emphasis on the study of legume root system contributions to soil physical conditions and soil nitrogen availability to successive crops. This report clearly demonstrates that alfalfa root systems had a much greater impact on soil nitrogen retention than the alfalfa shoot mulch. Living alfalfa stands increased soil organic matter levels compared to bare fallows, especially in the Bt_1 horizon. Total amounts of nitrogen present in alfalfa crowns and roots in October 1996 following two years of growth averaged 97 kg N ha^{-1} without alfalfa shoot mulch and 133 kg N ha^{-1} when alfalfa shoot mulch was applied. Application of alfalfa shoot mulch did not increase SOM contents. Alfalfa shoot mulch generated only transient increases of soil mineral N contents, which proved to be easily lost by leaching. One measurement also suggested that alfalfa shoot mulch increased soil denitrification rates. Nevertheless, when shoot mulch was applied to living alfalfa stands, herbage yields were increased, while nitrate leaching rates appeared unchanged. These findings indicate that little to no alfalfa shoot should be applied or left on the soil surface, unless a living root system is present to intercept mineral N fluxes through the soil profile. In addition, this research shows that saturated hydraulic conductivities (K_s), total and macroporosities, and water recharge rate of the soil

profile were significantly increased by alfalfa root systems compared to bare fallow soils. Root turnover and disappearance rates were significantly correlated to K_s. This suggests that killing an alfalfa stand increases water movement through soils, which potentially increases nitrate leaching to the groundwater. Consequently, fast mineralization of alfalfa shoot tissues, together with enhanced water flow by alfalfa RIMs, present a potential risk of groundwater contamination.

Improved soil aggregation by alfalfa shoot mulch applications to soils under alfalfa stands and bare soil fallows constituted the principal contribution of alfalfa shoots to sutainable soil conditions. These results suggest that legume mulch could be used for transferring biomass to high N-requiring crops growing on highly erosive soils. Hence, this study demonstrates that applications of alfalfa mulch have the potential to augment soil water contents, increase aggregate stability and contribute substantial amounts of mineralized N to soils.

Corn nitrogen requirements during a dry year were entirely met by mineralization of alfalfa plant tissues and soil organic matter, following one year of alfalfa. Moreover, extractable soil mineral nitrogen contents increased by 30 to 40 kg ha^{-1} over the corn growing season. Decomposition of alfalfa shoot and root tissues, following the spray-killing in early May, generated nitrate concentrations in the soil solution of Bt_1 horizons greater than 60 mg NO_3-N l^{-1}. Nitrate concentations leached to soil depths greater than 2 m in the Winter following corn planted to alfalfa exceed EPA's recommendadtion of 10 mg l^{-1}. Mineralized N in excess of corn requirements together with higher N leaching suggest that

alfalfa shoots were superfluous and should have been removed from plots when the stand was killed in the Spring.

This research suggests that the distribution of the corn root system within soil horizons and the recolonization of alfalfa RIMs by corn roots are critical factors influencing corn nutrition and nitrate leaching. Corn roots developing in a previously cropped alfalfa field recolonized alfalfa RIMs and decomposing roots at more than 40%. Corn root systems growing in soils previously cropped with alfalfa presented similar patterns of root distribution by horizons to previous alfalfa root systems. Preferential corn root distribution and recolonization potentially interacted with the temporal release of NO_3-N by decomposing alfalfa roots by placing the new corn root in a nitrate-enriched environment. Consecutive corn monocropping did not display consistent root distribution patterns throughout the soil profile from one year to the next.

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