Available online at www.sciencedirect.com
SCIENCE DIRECT®

Agriculture, Ecosystems and Environment 109 (2005) 97–106

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Specific contributions of decaying alfalfa roots to nitrate leaching in a Kalamazoo loam soil

Yasemin Kavdır[a,*], Daniel P. Rasse[b], Alvin J.M. Smucker[c]

[a] Canakkale Onsekiz Mart University, Agricultural Faculty, Soil Science Department, 17020 Canakkale, Turkey
[b] Laboratoire BioMCo, Institut National de la Recherche Agronomique, 78850 Thiverval-Grignon, France
[c] Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI 48824, USA

Received 24 September 2003; received in revised form 24 January 2005; accepted 8 February 2005

Abstract

Alfalfa (*Medicago sativa* L.) contributes 430 million kg N year^{-1} to the US Corn-Belt soils, according to a 1991 survey. Minimizing leaching losses from these very large N inputs requires a better understanding of the specific root dynamics that relate to the shoot-borne nitrates which have been reported to develop throughout many soil profiles. The objective of the present study was to determine the impact of decaying alfalfa roots on nitrate inputs to soils and on soil hydraulic conductivity properties which affect nitrate leaching.

An experiment was initiated in 1994 and data for this report were taken from research on a Kalamazoo loam soil (fine-loamy, mixed, mesic Typic Hapludalf) at the KBS/LTER (long-term ecological research) site in southwestern Michigan, during the period from 1996 through 1997. Soil extractable nitrate (NO_3-N) and ammonium (NH_4-N) were monitored to soil depths of 150 cm and soil soluble NO_3-N and NH_4-N were monitored by suction lysimeters to the depth of 65 cm. Saturated hydraulic conductivity (K_{sat}) of soil was measured by the double-ring infiltrometer method.

Following glyphosate termination of the alfalfa stands, nitrate-N released from mineralized alfalfa roots plus shoots totaled 75 kg ha^{-1}. Alfalfa roots generated 36 kg ha^{-1} and alfalfa shoots generated 39 kg ha^{-1} which accumulated in the Ap horizons from April to July in 1997. The presence of decaying alfalfa roots in the profile quadrupled K_{sat} values as compared to bare fallow soils. Nitrates released from decomposing alfalfa roots combined with root-enhanced hydraulic conductivities dramatically increased NO_3-N leaching following the termination of alfalfa stands. NO_3-N leaching to deeper horizons approached 83 kg ha^{-1} in root treatments and 144 kg ha^{-1} in the root plus shoot treatments during the period from April to December, following alfalfa termination. Our data suggest that under temperate climate such as that of Michigan, groundwater contamination by nitrates can be reduced by terminating alfalfa stands immediately before spring-planting of the subsequent row crop, which can absorb the large quantities of N leaking from decomposing shoots and roots of the legume.

Keywords: Alfalfa; Roots; Suction lysimeters; Nitrate leaching; Hydraulic conductivity

* Corresponding author. Tel.: +90 286 2180018/1314; fax: +90 286 2180545.
E-mail address: kavdirya@comu.edu.tr (Y. Kavdır).

0167-8809/$ – see front matter
doi:10.1016/j.agee.2005.02.020

1. Introduction

Alfalfa and most legumes symbiotically fix N_2 from the atmosphere and absorb inorganic N ions from the soil profile. Thirty-six years ago it was reported by Stewart et al. (1968) that alfalfa cropping was an excellent crop to prevent groundwater contamination by nitrates. Russelle et al. (2001) reported that total N removal by non-N_2-fixing alfalfa shoots from a N spill site averaged 972 kg N ha^{-1} in 3 years. In spite of a high soil N removal capacity by alfalfa, termination of alfalfa growth appears to result in great losses of plant N into the soil. Therefore, neglecting the alfalfa N contribution to the soil results in an overestimation of the fertilizer requirement for the succeeding crop. This results in the accumulation of excess NO_3 in the soil and increasing the leaching potential of soil N. Termination of alfalfa with herbicide applications is a common practice for no tillage systems. Bullied and Entz (1999) reported that the termination of alfalfa with herbicides created alfalfa residues that serve as a mulch groundcover, reducing soil erosion and moisture loss.

Alfalfa roots and crowns contain from 85 to 115 kg N ha^{-1} (Hesterman et al., 1986; Rasse et al., 1999). Quantities of NO_3-N released following alfalfa termination ranged from approximately 100 to 250 kg N ha^{-1} (Hesterman et al., 1987; Mohr et al., 1999). In addition, because alfalfa root systems increase the soil hydraulic conductivity (Meek et al., 1989), the risk of NO_3-N leaching is further increased, especially by no-till systems containing surface residues of decomposing alfalfa. Predicting and understanding the timing, amount, and fate of N released following alfalfa termination is complex. Therefore determinations of the sources of inorganic N, whether from soil organic matter, alfalfa roots, or shoots provides a tool for improving synchrony between N release from alfalfa residues and the N needs of a subsequent crop. The objective of this study was to quantify N released from decomposing alfalfa roots following the termination of alfalfa plants.

2. Materials and methods

2.1. Experimental design and treatments

An experiment was initiated in 1994 and data for this report were taken from research on a Kalamazoo loam soil (coarse-loamy, mixed, mesic Typic Hapludalf) at the long-term ecological research (LTER) site on the Kellogg Biological Station (KBS) in southwestern Michigan during the period from 1996 through 1997. The experiment was conducted on 12 plots (6 m × 10 m) and treatments were: (1) bare fallow control (BFC), (2) living alfalfa stands where shoots were removed at harvest and roots remained in the soil in situ (AR), and (3) living alfalfa stands with shoots returned to the plot surface at each harvest prior to stand termination (ARS). Each treatment was replicated four times in a randomized complete block design. BFC treatments were maintained free of weeds by applying glyphosate (*N*-(phosphonomethyl)-glycine) at the rate of 7 l ha^{-1}, every 6 weeks from April to August of each year (Rasse et al., 1999). Alfalfa was planted in AR and ARS treatments at the rate of 22 kg ha^{-1} in August 1994.

Alfalfa was harvested three times per year at 5 cm above the soil and shoots were removed from the AR treatment. Shoots from ARS treatments were cut and uniformly applied on the soil surfaces. Plots were separated using plastic surface barriers to prevent run off and run on between adjacent plots (Rasse et al., 1999).

Early in the spring of 1997, glyphosate application terminated all alfalfa growth. We observed very little alfalfa shoot biomass in April 1997 after the crop had been terminated. Therefore, we considered this amount to be negligible. Following termination of the alfalfa crop, all plots of all treatments were maintained plant-free during the growing season by making two applications of glyphosate during the successive 7-month period. Busse et al. (2001) reported no detrimental effect of glyphosate applications on microbial community or N mineralization when applied at manufacturer's recommended concentrations.

2.2. Measurements

Alfalfa biomass yields were estimated at each of the 1996 harvests by sampling a non-disturbed 4 m × 4 m area reserved for this purpose. Alfalfa shoot mulch biomass remaining on the soil surface was sampled in October 1996, as explained in Rasse et al. (1999). There was a total of 480 soil samples removed from the plots to depths of 150 cm on 12

Table 1
Alfalfa shoot and root biomass and their associated total N contents in April 1997[a]

	Total yield		Total N in biomass	
	AR[a] (kg ha^{-1})	ARS (kg ha^{-1})	AR (kg ha^{-1})	ARS (kg ha^{-1})
Root (0–60 cm)	5045 ± 702[b]	6080 ± 546	100	102
Total shoot application[b]	–	8901	–	329
Total			100	431

[a] AR and ARS are alfalfa root and alfalfa root plus shoot treatments, respectively.
[b] Shoot biomass values were the sum of three different cutting dates in 1996. Standard errors for $n = 4$.

October 1996, 29 April 1997, 7 July 1997 and 17 December 1997 using a hydraulic Giddings probe (Giddings Machines Co., Ft. Collins, CO), equipped with a 8.9 cm-diameter probe. Two core samples were taken from each plot. Cores were divided into depths representing the A_p, Bt_1, Bt_2, C_1 and C_2 horizons (Table 1). Each core was taken in April 1997 and divided vertically into equal halves, using a knife to cut through a split PVC pipe surrounding the soil core. The first half of each sampled horizon, containing roots, was stored at 4 °C until roots were washed free of soil. Inorganic N was extracted and quantified from the second half of the soil core.

Inorganic N extractions were conducted on 20 g field-moist subsamples, which were placed in 250 ml Erlenmeyer flasks containing 50 ml of 1N KCl extraction solution and shaken to equilibrium on a rotary shaker for 1 h. Clear solutions were obtained by filtering the soil slurry through Whatman No. 1 filter papers. Solutions were stored in 20 ml scintillation vials at 4 °C until analyzed for NO_3 and NH_4 by the cadmium reduction method using a QuickChem Automated Ion Analyzer (Lachat Instruments, 6645 West Mill Road, Milwaukee, WI). Roots were extracted from the soil matrix by the hydropneumatic elutriation method of Smucker et al. (1982).

Each field plot was equipped with three suction lysimeters (100 kPa high-flow, Model 1900, Soil Moisture, Santa Barbara, CA) installed at 45° angles into soil depths of 15, 35 and 60 cm. Water samples were collected from suction lysimeters 24–30 h after soil solutions equilibrated with the 0.07 MPa negative pressure. Samples were stored in 20 ml scintillation vials at 4 °C and analyzed in 1 week for NO_3 and NH_4 by the cadmium reduction method using a QuickChem Automated Ion Analyzer.

Average concentration values of NO_3-N plus NH_4-N (mg g^{-1} oven dry soil) were combined with soil bulk density for each horizon, adjusted to air-dry soil to calculate kg N ha^{-1} using the following equation:

$$\mathrm{kg\,N\,ha^{-1}} = \frac{\mathrm{mg\,N\,kg^{-1}} \times \mathrm{b.d.} \times \mathrm{thickness}}{100} \quad (1)$$

where b.d. = bulk density of soil horizon (kg m^{-3}), thickness = thickness of soil horizon (m).

Soil core samples were taken using a double-cylinder, hammer driven core sampler for measurement of bulk density (Blake and Hartge, 1986). Soil water contents of each horizon were estimated by time-domain reflectrometry (TDR) technology, using a Tektronix cable tester, model 1502C (Tektronix Inc, Beaverton, OR, U.S.A.). Volumetric soil water contents were calculated using the Topp equation (Topp et al., 1980). Detailed descriptions of the TDR probes and field implementation are provided by Rasse et al. (1999).

A double-ring infiltrometer with inner and outer rings of 0.3 and 0.6 m in diameter, respectively, was used to determine steady infiltration rates at a constant head (Reynolds et al., 2002) in June and September 1997. Two metal rings were inserted in the soil at a depth of 7 cm. The soil between the two rings was saturated while the inner-ring soil was covered with a plastic sheet. The inner ring was slowly filled with water to a 5 cm depth and the plastic cover was removed. Water level was maintained constant, by frequent additions, during the measurement. Measurements of the drop in water level were recorded in the inner ring and water was added to return the water head to original level. Hydraulic conductivity was estimated for the topsoil when the water flow rate in the inner ring had reached a constant rate. The water level of the outside ring was maintained similar to that of the inside ring by frequent additions.

Rainfall at the KBS-LTER site from April 97 to January 98 was 903 mm. On average, 60% of the annual precipitation occurs from April to October. Rainfall and maximum and minimum air temperatures recorded at KBS for the study period and 30-year averages are shown in Fig. 1.

2.3. Statistical analysis

Repeated measurement design (Winner et al., 1991) was used to determine effects of treatments, sampling time and sampling depth on soil extractable NO_3, NH_4 and total inorganic N. For this purpose, SPSS for windows (Version 11.0) and Minitab for windows (Version 13.0) statistical packages were used. K_{sat} values were analyzed by a PROC-GLM (General Linear Models) procedure using Statistical Analysis System (SAS, 1999). Fishers LSD test was used to separate means of measurements.

3. Results

3.1. Extractable soil inorganic nitrogen in soil profile

Variance analyses of extractable soil NO_3-N and NH_4-N values demonstrated a significant three-way treatment by depth by time interaction, with a $p < 0.01$ (data not shown). This indicates that the response of soil NH_4-N and NO_3-N to treatments

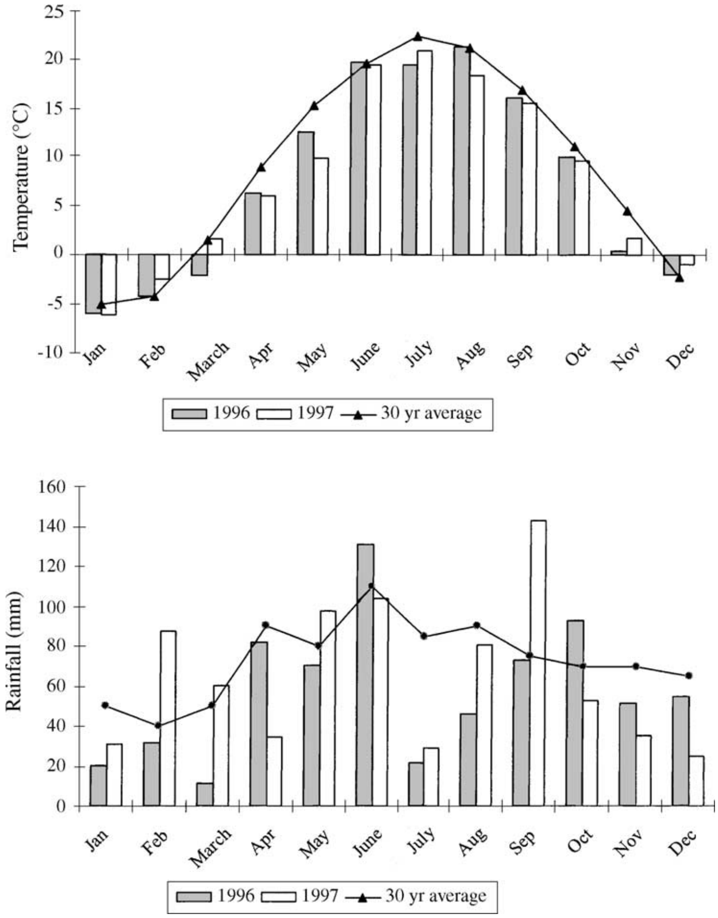

Fig. 1. Monthly and 30-year average air temperature and precipitation recorded at KBS, LTER site weather station in 1996 and 1997.

varied differently with time and soil depth, which calls for a separate interpretation of the results during each time period and soil depth. Periods of statistical analyses prior to and immediately after alfalfa stand termination, i.e. until April 1997, were analyzed separately from the successive period of July 1997, when alfalfa plants were decomposing.

Prior to alfalfa stand termination, soil NO_3-N contents were lower in alfalfa plots than in BFC plots, independent of shoot mulch application (Fig. 2A and B). Extractable NO_3-N values in the BFC increased from May to October 1996 due to the mineralization of soil organic matter during the summer and fall (Fig. 2A and B). However, continuous N uptake by the living alfalfa plants resulted in low extractable NO_3-N through the soil profile in October 1996 for AR and ARS treatments (Fig. 2B).

Three days after spray killing of alfalfa in April 1997, remaining shoots were cut and removed from root (AR) treatments and shoots remained in ARS treatments. Extractable soil NO_3-N contents ranged between 0.6 and 18 kg ha^{-1} of all treatments in April 1997 and no significant differences were observed among treatments for Ap, Bt_1 and Bt_2 horizons (Fig. 2C). Greater N content in C_1 and C_2 horizons under BFC treatments than other treatments in April 1997 suggested that more NO_3-N leached into deeper horizons in BFC treatment. As alfalfa roots and shoots decomposed, soil NO_3-N increased to 135 kg N ha^{-1} in the Ap horizon of ARS treatments by July 1997 (Fig. 2D). Ap horizons of ARS treatment gained 123 kg NO_3-N ha^{-1} from April to July of 1997 (Fig. 2C and D). In contrast, soil NH_4-N content decreased from April to July of 1997 (Fig. 3C and D). In the BFC treatment, mineralization was only that of the indigenous soil organic matter, which totaled 48 kg NO_3-N ha^{-1} (Fig. 2C and D). Therefore, 75 kg NO_3-N ha^{-1} were mineralized from alfalfa

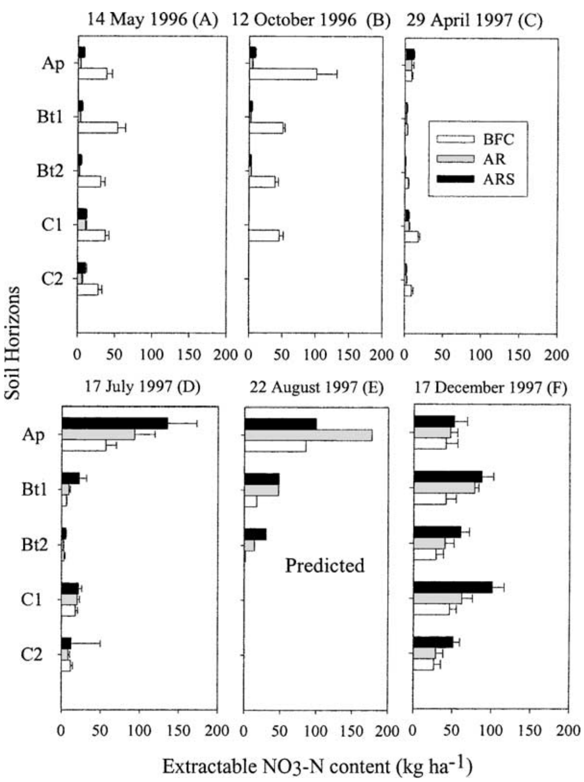

Fig. 2. Extractable NO_3-N contents of soil horizons under bare fallow (BFC), alfalfa root (AR), and alfalfa root plus shoot mulch (ARS) treatments. Bars represent standard errors.

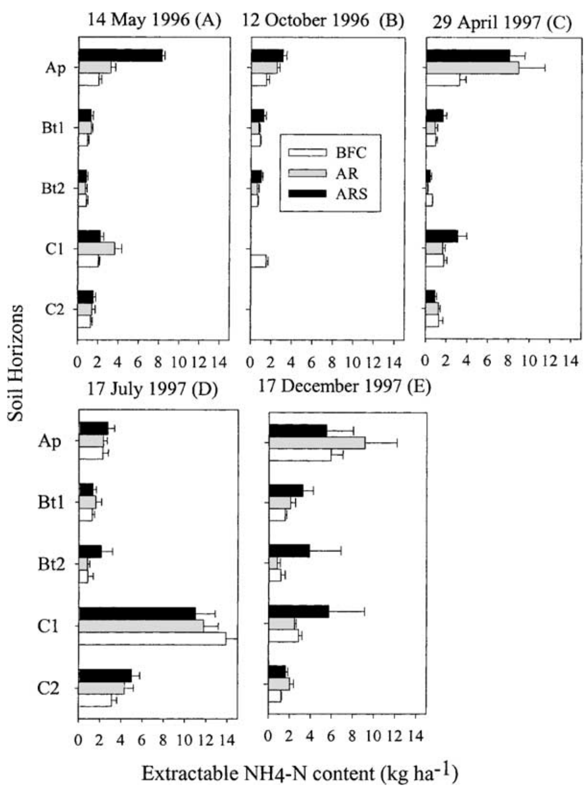

Fig. 3. Extractable NH_4-N contents of soil horizons under bare fallow (BFC), alfalfa root (AR), and alfalfa root plus shoot mulch (ARS) treatments. Bars represent standard errors.

roots plus shoots located in the Ap horizon within 3 months of herbicide termination of alfalfa. NO_3-N mineralization from alfalfa roots alone was 36 kg ha^{-1}in the Ap horizons during the period from April to July of 1997 (Fig. 2D). By difference, NO_3-N release by decomposing alfalfa shoots averaged 39 kg ha^{-1} during the same period of time.

The fairly uniform pattern of inorganic NO_3-N distribution to greater soil depths in December 1997 (Fig. 2F) indicates that deep N leaching was pervasive suggesting an increase in inorganic N accumulation occurred between the July and December 1997 measurements. We estimated the extractable NO_3-N in August, based on the soluble NO_3-N measured in suction lysimeters. A comprehensive interpolation was possible, using the strong and positive correlation ($r^2 = 0.88$, $p < 0.05$) identified between the extractable NO_3-N of soil samples collected on 17 July and the soluble soil NO_3-N from suction lysimeter samples, collected in 10 July 1997 (Fig. 4). These dates were chosen for the correlation because sampling of both occurred within 1 week. Using the equation derived from this correlation, we estimated the extractable NO_3-N for 22 August 1997 (Fig. 2E). Predicted values in August showed that root-derived NO_3-N values exceeded those of roots plus shoots (ARS) and the estimated extractable NO_3-N content was greater than 175 kg N ha^{-1} in the Ap horizon for the alfalfa root (AR) treatments. Declines in extractable NO_3-N levels for all treatments were observed in the December of 1997 (Fig. 2F).

Extractable NO_3-N contents of the Ap horizon decreased from 133 to 54 kg ha^{-1} during the period from July to December of 1997 in ARS treatments (Fig. 2D and F). Proportionally less NO_3-N was leached from the Ap horizons of the BFC compared to the AR and ARS treatments where alfalfa was grown, suggesting the hydraulic conductivities of these soils were modified by the presence or absence of alfalfa plant roots.

NO_3-N leaching to deeper C_1 and C_2 horizons reached up to 83 kg ha^{-1} in treatment AR and 144 kg ha^{-1} in treatment ARS during the period from alfalfa termination (April) to December (Fig. 2C and F).

Extractable soil NH_4-N values ranged from 0.19 to 13.89 kg ha^{-1} (Fig. 3A–F). Ammonium-N levels in springs of 1996 and 1997 were significantly higher in ARS than BFC treatments. The greater NH_4-N contents in Ap horizon of ARS treatments (Fig. 3A–C) are attributed to surface residue accumulation after alfalfa shoot applications. In July 1997, extractable NH_4-N contents in C_1 and C_2 horizons were greater than those in the upper soil horizons (Fig. 3D) indicating that inorganic N in the coarse-textured C horizon was not being nitrified to nitrate.

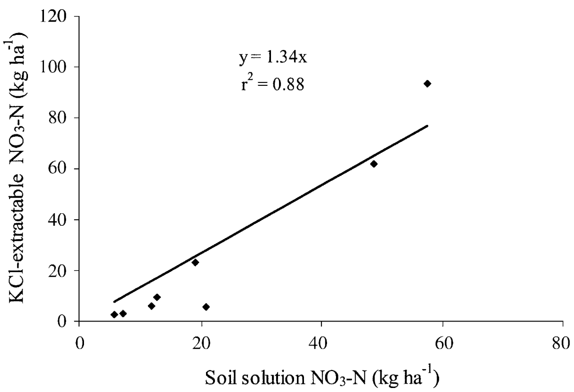

Fig. 4. Relationship between soil solution NO_3-N content and KCl-extractable NO_3-N content of soil in July 1997.

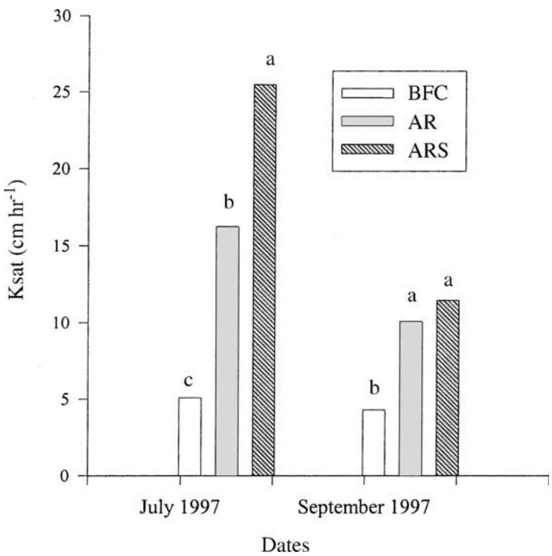

Fig. 5. K_{sat} values of soils under bare fallow (BFC), alfalfa root (AR), and alfalfa root plus shoot mulch (ARS) in 1997. Means followed by the same letter within measurement time are not significantly different according to Fisher's LSD (0.05).

3.2. Saturated hydraulic conductivity

Decomposing and shrinking alfalfa root systems after termination of alfalfa increased the saturated hydraulic conductivities (K_{sat}) in July 1997 by nearly 200 and 400% when shoot mulches were absent or present, respectively (Fig. 5). K_{sat} values were about 25 cm h^{-1} in ARS treatments. This dying root effect, coupled with surface cover by shoots appeared fairly transient as K_{sat} values in AR and ARS plots decreased rapidly between July and September 1997, yet remained higher than the BFC soils without plants (Fig. 5). Higher K_{sat} values in the more moist ARS treatments may have resulted in greater leaching and lower soluble NO_3 values retained in the Ap horizon during July and September 1997.

3.3. Soil solution inorganic nitrogen increases

The dominant form of soluble inorganic-N in the Kalamazoo soils of this study was NO_3-N. When living alfalfa was present in the soil, soil solution NO_3-N contents were lower than the bare fallow control plots in all three soil horizons (Fig. 6). Soil solution NO_3-N contents varied between 0 and 4.6 kg NO_3-N ha^{-1} for AR and ARS treatments during the summer of 1996. Spray killing the standing alfalfa dramatically increased soluble inorganic N values of AR and ARS

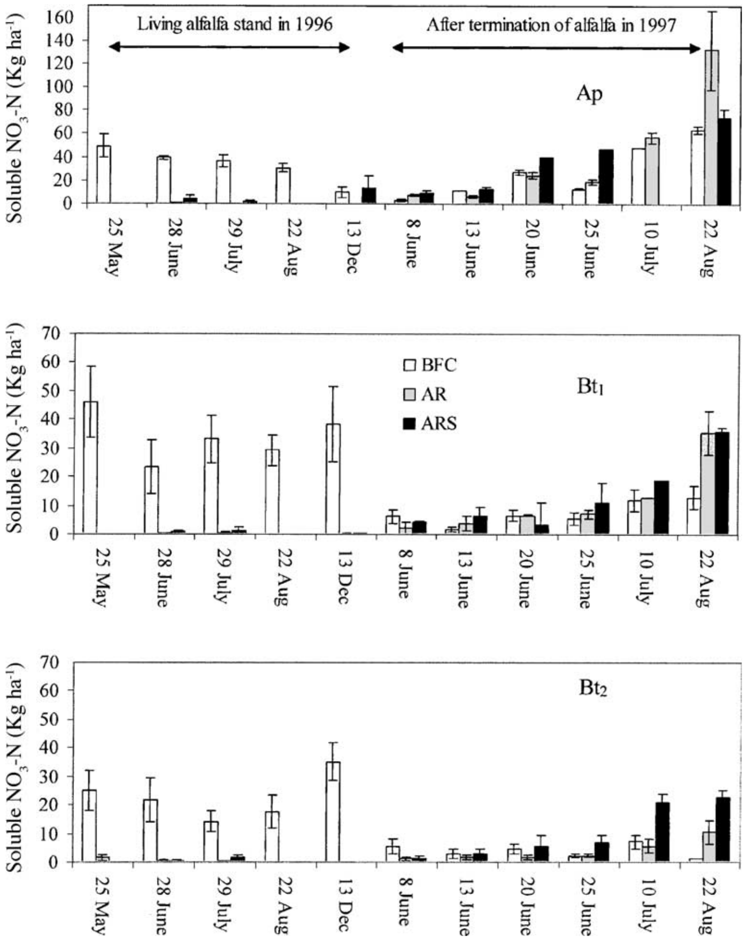

Fig. 6. Soil solution NO_3-N contained in the Ap, Bt_1 and Bt_2 horizons (0.65 m) of soils under bare fallow (BFC), alfalfa root (AR), and alfalfa root plus shoot mulch (ARS), in 1996 and 1997.

treatments later in July and through August, 1997 to values above the bare fallow control (Fig. 6). Soil solution NO_3-N contents of Ap horizons increased from 7 to 132 kg N ha^{-1} and from 9 to 74 kg N ha^{-1} for AR and ARS treatments, respectively, during the period from 8 June to 22 August 1997 (Fig. 6). In spite of lower NO_3-N contents in the Ap horizon of ARS than AR treatments, more NO_3-N was accumulated in Bt_2 horizon in ARS treatment in August. Mineralization of soil organic matter and the accumulation of alfalfa shoot N in the Ap horizons increased from June to August 1997. However, no significant changes were observed in the Bt_1 horizons (Fig. 6).

4. Discussion

Our study confirms that substantial amounts of organic nitrogen mineralized to NO_3 may become susceptible to leaching following the termination of alfalfa stands. Although these data were collected in one set of environmental conditions (loam soil of temperate Michigan), like any other field trial study, they fully corroborate results from El-Hout and Blackmer (1990), Peterson and Russelle (1991) and Rasse and Smucker (1999).

Additionally, this study demonstrated that terminated alfalfa stands generated comparatively more soil nitrate within the soil profiles than inorganic N generated by mineralization of SOM in bare fallow systems without fertilizer N inputs during the previous 4 years.

Comparisons of extractable NO_3-N showed that mineralization in the Ap horizons from alfalfa roots (AR) was 36 kg ha^{-1} during the period from April to July of 1997. This value is greater than the previous results reported by Biederbeck et al. (1995), who found that 3 and 15 kg ha^{-1} N were mineralized from green manures of field pea (*Pisum sativum* L.) and black lentil (*Lens culinaris* Medik.) during the 3 months following incorporation into surface soils. Compared to other legumes, mineralization rates of N from alfalfa root + shoots were higher in the Kalamazoo loam under a no-till system. Nitrogen mineralization rates of alfalfa shoots (ARS) was 39 kg NO_3-N ha^{-1} in Ap from April to July of 1997. Therefore, mineralization of alfalfa roots produced as much NO_3-N as alfalfa shoots in Kalamazoo loam.

Several explanations may account for alfalfa contributions to soil N pools. First, alfalfa plant tissues and SOM appear to mineralize relatively slowly in a no-till system. Therefore, it is conceivable that their combined contributions to soil mineral N pools continued across multiple years. During this study, it was observed that NO_3 was released in the soil profile for at least 8 months following the termination of the stand. In a parallel experiment, conducted on a similar soil type, Rasse and Smucker (1999) observed that the peak of NO_3 mineralization occurred only 8 months after the termination of the stand, although corn was planted immediately following the alfalfa stand termination.

Kavdir (2000) previously reported that leached N was only 3 kg N ha^{-1} immediately after spray killing of alfalfa plants in April. Even with no N fertilization, cumulative N leaching approached to 65 kg N ha^{-1} in large non-disturbed profile lysimeters installed in no-till treatments. After 19 months, concentrations of 105 kg N ha^{-1} were measured in lysimeters installed in conventionally tilled treatments. It appears that when alfalfa herbage is incorporated in the soil, release of N is accentuated (Schroth, 2003). Therefore when conservation tillage is applied to a standing alfalfa crop, more inorganic N becomes available to the succeeding row crops, reducing N mineralization rates and subsequent NO_3-N losses below the rooting zone.

More N was mineralized in Kalamazoo soils when alfalfa plants were present. Greater production and leaching of soil N in this soil appeared to result from the combined activities of alfalfa plant decomposition and root induced macroporosities resulting from decomposing alfalfa roots. Hoyt and Leitch (1983) reported that forage legume contribute substantial amounts of available N to soils during 2–3 years following stand termination. Our results confirm that maximum NO_3 accumulations of inorganic N were distributed throughout the soil profile 8 months after terminating a standing alfalfa crop.

Greater K_{sat} rates under alfalfa stands might induce higher NO_3 losses from the soil as compared to a bare fallow control, which potentially accounts for an apparent smaller contribution by alfalfa than it is expected. Our results demonstrated a transient nature of increasing soil hydraulic conductivity following alfalfa termination. Very high K_{sat} values were observed in the field, when compared to those from previous laboratory measurements (Rasse et al., 2000). They reported that soil K_{sat} values for bare soils were 1.14 cm h^{-1} in October 1996, before the alfalfa crop was spray killed. These values were 3.5 times lower than the K_{sat} values obtained from field measurements in September 1997, 5 months after the alfalfa crop was spray killed. Meek et al. (1992) found that maximum K_{sat} values for undisturbed cores were 9 cm h^{-1} for Wasco sandy loam when living alfalfa roots were present in the soil. One reason for these lower values obtained in the laboratory experiments may be the exclusion of alfalfa plants and big roots from the soil cores at the time of sampling. Decomposition of alfalfa roots following stand termination with glyphosate, created preferential flow channels and increased K_{sat} values in alfalfa treatments in a manner similar to those reported for decomposing roots of maize and ryegrass (Smucker et al., 1995). Ellsworth et al. (1991) reported that aging and decaying roots directly enhanced the preferential flow of water and solutes. Root death and decomposition created additional macropores in the soil profile. Therefore, lower soluble NO_3-N contents in ARS treatments than AR treatments, during August, may have been the result of preferential N leaching from ARS treatment, as indicated by the higher K_{sat} values in the ARS treatments. Mohr et al. (1999) reported that unless other plants invade the field, NO_3-N would be expected to increase when alfalfa plants die. Cavers (1996) found that the K_{sat} through soil profiles under alfalfa stands was about 10 times greater than under small grain rotations on a clay soil in Manitoba. The combination of N release from alfalfa roots and increased potential for soil water infiltration and bypass flow would dramatically increase NO_3-N losses (Bouma, 1991). Using a double-ring infiltrometer, Dao (1993) reported that no-till soils with surface residues significantly increased infiltration relative to traditional tillage methods. The residue cover appeared to decrease surface soil crusting by surface protection from raindrop impacts. Resultant lower bulk densities of residue covered surface soils permitted higher infiltration.

Additional denitrification rates under alfalfa stands and especially alfalfa shoot mulching (Rasse et al., 1999) may have established extremely low quantities of soil nitrate in alfalfa treated plots before alfalfa was spray killed. Minimum nitrate levels could have caused substantial redistribution and utilization of inorganic N by the microbial populations in the soil before nitrate leaching occurred.

5. Conclusion

In the temperate climate of Michigan, we observed little leaching risk of nitrate under living alfalfa stands. However, nitrate leaching losses following destruction of a standing alfalfa crop are highly significant when soil temperatures are high enough to promote nitrification. High nitrogen contents in both the roots and shoots of alfalfa contribute to nitrate accumulations in surface horizons. Combinations of high inorganic soil N levels and more numerous soil macropores, established during a 2–3-year stand of alfalfa, appear to cause soils to become more vulnerable to excessive nitrate leaching, especially during seasons when subsequent crops are not large enough to absorb the high concentrations of inorganic soil N following alfalfa termination. These data also demonstrate that less N accumulates in soils when alfalfa shoots are removed than when they are returned to the soil surface. Therefore, care must be taken to best synchronize the spray killing of alfalfa with the planting of corn and other subsequent crops. The asynchronization of soil nitrate availability and leaching losses reported in this study, suggest more soil nitrates may be absorbed by succeeding crops, if Roundup-Ready corn was directly seeded into a stand of alfalfa and the alfalfa plants spray killed directly over the crop. Then as the row crop becomes large enough to absorb additional N from decomposing alfalfa cover crops, the entire alfalfa crop could be spray killed, as reported for cover crops and Roundup-Ready corn (Kinyangi et al., 2001).

Acknowledgements

Financial support provided by the NSF/LTER program at the Michigan State University. Kellogg Biological Station is gratefully acknowledged.

References

Biederbeck, V.O., Bouman, O.T., Campbell, C.A., Bailey, L.D., Winkleman, G.E., 1995. Nitrogen benefits from four greenmanure legumes in dryland cropping systems. Can. J. Plant Sci. 20, 307–315.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Agron. Monogr. 9.. 2nd ed. ASA and SSSA, Madison, WI, pp. 363–375.

Bouma, J., 1991. Influence of soil macroporosity on environmental quality. Adv. Agron. 46, 1–37.

Bullied, W.J., Entz, M.H., 1999. Soil water dynamics after alfalfa as influenced by crop termination technique. Agron. J. 91, 294–305.

Busse, M.D., Ratcliff, A.W., Shestak, C.J., Powers, R.F., 2001. Glyphosate toxicity and the effects of long-term vegetation control on soil microbial communities. Soil Biol. Biochem. 33, 1777–1789.

Cavers, C.G., 1996. Characteristics of Red River clays pertaining to vertisolic criteria and macropore flow. M.S. Thesis. University of Manitoba, MB.

Dao, T.H., 1993. Tillage and winter wheat residue management effects of water infiltration and storage. Soil Sci. Soc. Am. J. 57, 1586–1595.

Ellsworth, T.R., Jury, W.A., Ernst, F.F., Shouse, P.J., 1991. A three-dimensional field study of solute transport through unsaturated, layered, porous media. 1. Methodology, mass recovery, and mean transport. Water Resour. Res. 27, 951–965.

El-Hout, N.M., Blackmer, A.M., 1990. Nitrogen status of corn after alfalfa in 29 Iowa fields. J. Soil Water Conserv. 44, 240–243.

Hesterman, O.B., Sheaffer, C.C., Barnes, D.K., Lueschen, W.E., Ford, J.H., 1986. Alfalfa dry-matter and nitrogen-production, and fertilizer nitrogen response in legume–corn rotations. Agron. J. 78, 19–23.

Hesterman, O.B., Russelle, M.P., Sheaffer, C.C., Heichel, G.H., 1987. Nitrogen utilization from fertilizer and legume residues in legume–corn rotations. Agron. J. 79, 726–731.

Hoyt, P.B., Leitch, R.H., 1983. Effects of forage legume species on soil moisture, nitrogen and yield of succeeding barley crops. Can. J. Soil Sci. 63, 125–136.

Kavdir, Y., 2000. Distribution of cover crop N retained by soil aggregates in rye–corn agroecosystem. Ph.D. Thesis. Michigan State University, Michigan.

Kinyangi, J.M., Smucker, A.J.M., Mutch, D.R., Harwood, R.R., 2001. Managing cover crops to recycle nitrogen and protect groundwater. Mich. State Univ. Ext. Bull. E-2763, Michigan.

Meek, B.D., Rechel, E.A., Carter, L.M., DeTar, W.R., 1989. Changes in infiltration under alfalfa as influenced by time and wheel traffic. Soil Sci. Soc. Am. J. 53, 238–241.

Meek, B.D., Rechel, E.R., Carter, L.M., DeTar, W.R., Urie, A.L., 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. Soil Sci. Soc. Am. J. 56, 908–913.

Mohr, R.M., Entz, M.H., Janzen, H.H., Bullied, W.J., 1999. Plant-available nitrogen supply as affected by method and timing of alfalfa termination. Agron. J. 91, 622–630.

Peterson, T.A., Russelle, M.P., 1991. Alfalfa and the nitrogen cycle in the corn belt. J. Soil Water Conserv. 46, 229–235.

Rasse, D.P., Smucker, A.J.M., 1999. Tillage effects on soil nitrogen and plant biomass in a corn–alfalfa rotation. J. Environ. Qual. 28, 873–880.

Rasse, D.P., Smucker, A.J.M., Schabenberger, O., 1999. Modifications of soil nitrogen pools in response to alfalfa root systems and shoot mulch. Agron. J. 91, 471–477.

Rasse, D.P., Smucker, A.J.M., Santos, D., 2000. Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Sci. Soc. Am. J. 64, 725–731.

Reynolds, W.D., Elrick, D.E., Youngs, E.G., 2002. Single-ring and double or concentric ring infiltrometer. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Physical Methods, Book Ser. 5. SSSA, Madison, WI, pp. 821–826.

Russelle, M.P., Lamb, J.F.S., Montgomery, B.R., Elsenheimer, D.W., Miller, B.S., Vance, C.P., 2001. Alfalfa rapidly remediates excess inorganic nitrogen at a fertilizer spill site. J. Environ. Qual. 30, 30–36.

SAS, 1999. SAS/STAT Users Guide, vol. 2, Version 6th ed. SAS Institute, Cary, NC.

Schroth, G., 2003. Decomposition and nutrient supply from biomass. In: Schroth, G., Sinclair, F.L. (Eds.), Trees, Crops and Soil Fertility. CAB International, Wallingford, pp. 131–150.

Smucker, A.J.M., McBurney, S.L., Srivastava, A.K., 1982. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. Agron. J. 74, 500–503.

Smucker, A.J.M., Richner, W., Snow, V.O., 1995. Bypass flow via root-induced macropores (RIMS) in subirrigated agriculture. In: Proceedings of the Conference on Clean Water Clean Environment for the 21st Century, vol. III: Practices, Systems, and Adoption, Kansas City, MO, pp. 255–258.

Stewart, B.A., Viets Jr., F.G., Hutchinson, G.L., 1968. Agriculture's effect on nitrate pollution of groundwater. J. Soil Water Conserv. 23, 1–15.

Topp, G.C., Davis, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. 16, 574–582.

Winner, B.J., Brown, D.R., Michels, K.M., 1991. Statistical Principles in Experimental Design, 3rd ed. McGraw-Hill, p. 1057.