Soil water and nitrate fluxes modifications by alfalfa and corn root systems
Modification des flux d'eau et de nitrates par les systèmes racinaires de la luzerne et du maïs

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Effects of alfalfa root systems on soil physical properties, soil nitrate leaching and corn nutrition were investigated in two separate experiments conducted on Kalamazoo loam soils (coarse-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 both experiments 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 populations from in situ minirhizotron techniques, and 5) plant biomass and yields. Soil physical properties were analyzed in the alfalfa/bare fallow experiment, after two years of treatment.

The presence of alfalfa root systems significantly increased saturated hydraulic conductivity, and total and macro porosity of soils, compared to bare fallow. Living alfalfa root systems were very efficient in preventing nitrate leaching year round, with soil solutions generally kept below 1ppm of NO$_3^-$-N. Second year alfalfa stands averaged 26 and 76 kg N ha$^{-1}$ in the crowns and roots, respectively. Alfalfa shoots had little impact on soil nitrate contents, compared to root systems. Nitrogen released from spring spray-killed alfalfa was sufficient to cover all subsequent corn crop requirements and produce an excess of 20 kg of mineral nitrogen per hectare by the fall of the same year. Root densities per horizons of corn planted after alfalfa mimicked alfalfa root distributions, while no consistent pattern could be observed for corn after corn or alfalfa after corn. An excess of 40% corn roots recolonized alfalfa root induced macropores, which proved significantly higher than root recolonization of corn after corn or alfalfa after corn.

Introduction

Sustainable production on nitrogen-conservative agricultural soils is increasingly sought by agronomists and environmentalists. In the American corn belt alfalfa (*Medicago sativa* L.) dinitrogen fixation contributes to N inputs of more than 1 billion kg N yr$^{-1}$ (Peterson and Russelle, 1991). Mineralized nitrogen from alfalfa plants contributes most of the nitrogen required by the
succeeding corn crop (Fox and Piekielek, 1988). Though little nitrate leaching has been reported under living alfalfa stands (Peterson and Russelle, 1991), substantial N losses by deep leaching were observed in soils following moldboard incorporation of alfalfa. Consequently, best management practices for alfalfa, in rotation with corn (\textit{Zea mays} L.), require the maximum absorption of alfalfa-generated nitrogen by corn roots in order to minimize nitrate leaching.

Root system distributions in the soil profile are an important factor in the determination of water and nutrients available to plants (Kuchembuch and Barber, 1987). Modified distributions of corn root systems within the soil profile have been observed under contrasting fertilizer rates (Anderson, 1987), irrigation (Robertson, 1980), and tillage management studies (Anderson, 1987; 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 heterogeneous pore networks for root distribution. This article summarizes two separate experiments investigating the specific contribution of alfalfa root systems to soil N pools and soil hydraulic properties and their subsequent effect on the following corn crop and its root system distribution.

Material and Methods

Two field experiments were conducted at the Long-Term Ecological Research site of the Kellogg Biological Station on Kalamazoo loam soils (coarse-loamy, mixed, mesic Typic Haplustalf) in southwestern Michigan from 1994 to 1996. In the first experiment, 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. The alfalfa plots were harvested 3 times in each of the 1995 and 1996 growing seasons. The second field experiment was conducted in conventional tillage (CT) and no-tillage (NT) plots under a corn-alfalfa rotation equipped with undisturbed, in situ, large monolith lysimeters. 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. Drainage flows and nitrate loads leaching from the lysimeters were monitored over the three-year period. Measurements in both experiments 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 (TDR), 3) root biomass extracted from deep probe samples, 4) root populations from video recordings of \textit{in situ} minirhizotrons, and 5) plant biomass, plant nitrogen and yields. Soil physical properties were analyzed in the alfalfa/bare fallow experiment, after two years of treatment. Root recolonization assessments were conducted by simultaneous comparison of identical minirhizotron frames, 1.8 x 1.35 cm each, taken one growing season apart.

Results and Discussion

\textit{The alfalfa root system as a source of soil nitrogen}

Total amounts of nitrogen present in alfalfa crowns and roots at the end of the 1996 growing season averaged 97 and 133 kg N ha\(^{-1}\) for A and AS respectively. Alfalfa shoots harvested in August 1996 contained 49 and 90 kg N ha\(^{-1}\) for A and AS respectively. Hence, by
the end of the second growing season, greater amounts of nitrogen were contained in the crown and roots than in the shoots of alfalfa. Alfalfa root systems were very efficient in preventing nitrate leaching year round, with soil solutions of the Bt and C horizons generally kept below 1 ppm of NO$_3$-N. In the absence of a living root system, suction lysimeter and soil extraction data indicate that most of the mulch-generated nitrogen was lost by deep leaching from late Fall to early Spring. The nitrogen applied as alfalfa shoot mulch, which approximated 585 kg N ha$^{-1}$ over the two-year period, did not significantly increase total soil nitrogen pools, whether applied to bare fallow or to alfalfa stands, and was lost by deep leaching. Alfalfa root systems significantly increased soil organic matter contents by 29% in the Bt horizons. Alfalfa shoot application increased denitrification of bare fallow and alfalfa treatments on 16 June 1996 by about 250 g N ha$^{-1}$ d$^{-1}$. These results demonstrate that the extensive root system of alfalfa prevented nitrate leaching while increasing N storage in the soil profile in the form of root tissue and increased soil organic matter contents. The aboveground biomass proved less beneficial than the roots in improving soil N status.

**Alfalfa root system modifications of soil hydraulic properties.**

Total and macro soil porosities were significantly modified by alfalfa root systems, but remained unchanged by shoot application. Highest total and macroporosities were observed in the A treatment (Table 1). Lowest total and macroporosities were observed in the B and BS treatments, respectively (Table 1). Total porosities were correlated to total soil carbon contents and root numbers in the Ap horizon. Alfalfa root systems significantly increased saturated hydraulic conductivities ($K_s$) (Table 1). These results confirm previous reports by Caron et al. (1996) and Meek et al. (1992). Lowest $K_s$ was observed in the BS treatment (Table 1). A significant correlation was observed between $K_s$ and root turnover rates in the upper 10 cm of the soil profile. Root turnover rates and disappearance had greater impacts on $K_s$ than living root densities. These results concur with the conclusion of Meek et al. (1992) stating that sufficient decomposition of alfalfa root tissues is necessary to create empty root-induced macropores (RIMs) which can contribute to the preferential flow of water through soils. In addition, using TDR technology, our studies showed that the water recharge rate of the soil profile improved significantly when alfalfa root systems were present.
Table 1. Saturated hydraulic conductivities (Ks), bulk densities (BD), total, macro and micro porosities 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.

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<td></td>
<td>cm hr⁻¹ Mg m⁻³</td>
<td>%</td>
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<tr>
<td>Total</td>
<td></td>
<td>Macro</td>
<td>Micro</td>
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<tr>
<td>B</td>
<td>1.14b</td>
<td>1.46a</td>
<td>38.7b 11.4ab 27.3b</td>
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<td>BS</td>
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<td>1.49a</td>
<td>39.0ab 10.0b 29.0a</td>
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<tr>
<td>A</td>
<td>1.64a</td>
<td>1.45a</td>
<td>41.0a 13.0a 27.9ab</td>
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<tr>
<td>AS</td>
<td>1.50a</td>
<td>1.46a</td>
<td>40.1ab 12.0ab 28.1ab</td>
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Factorial Analyses

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† Median reported, means separation test conducted on log-transformed data.
‡ Same letters indicate non-significant differences by Fisher’s LSD₀.₀₅.
*, **, *** Significant at P ≤ 0.05, 0.01 and 0.001 respectively, NS = non significant

Corn root system responses to soil water, and previous alfalfa root system

In a separate study, numbers of corn roots per m² in the Bt₁ horizon were consistently greater for NT than CT, in 1994 and 1996 (Figure 1). Corn root population in the Bt₁ horizon was significantly greater (P≤ 0.05) in the NT treatment during 1994. 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 appeared to promote root growth in deeper horizons. Maximum corn root growth in the Bt horizon occurred at locations subjected to the least amount of water stress earlier in the growing season (Figure 2). 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 (Robertson et al., 1980). Non irrigated corn presented similar to higher root populations at depths greater than 30 cm.

Corn roots in 1996 absorbed substantial amount of nitrogen fixed by alfalfa. Exported nitrogen by corn plants following alfalfa were 64% and 119% greater than following corn for non fertilized CT and NT plots, respectively (Figure 3). Distribution of the corn root system potentially affected the ability of individual corn roots to absorb nitrogen mineralized from decomposing alfalfa roots. Also, root-induced macropores (RIMs) of alfalfa potentially constitute preferential channels and lines of least resistance along which corn roots can grow more easily. Root distributions within the soil profiles, represented by the total root numbers for each individual minirhizotron tube, were compared for the 1993 to 1996 growing seasons. Correlation of root populations between two consecutive growing seasons were the following: r = -0.01 for corn (1994) after corn (1993), r = 0.11 for alfalfa (1995) after corn (1994), and r = 0.84** for corn (1996) after alfalfa (1995). Distribution of corn root systems (1996) was significantly correlated to the distribution of previous alfalfa root systems (1995). Corn root distributions
(1994) showed virtually no correlation with the root systems of the previous corn crop (1993). Root colonization of the Bt horizons by alfalfa (1995) was not influenced by corn root distribution in 1994. Root recolonization of decomposing roots along the RIMs, analyzed within the individual minirhizotron frames, showed different patterns for the three years of study. Root recolonization averaged 18% for corn after corn (1994), 22% for alfalfa after corn (1995) and 41% for corn after alfalfa (1996), across the two horizons and two tillage treatments. 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.

Figure 1. Corn root demographics per horizons in conventional tillage (CT) and no-tillage (NT) lysimeters. Standard errors for n =2.
Figure 2. Correlation between minimum volumetric soil water contents (SWCmin) reached before 1 July and root numbers observed in August of the same year, in the top Bt1 horizon of conventional tillage (CT) and no-tillage (NT) lysimeters.

Figure 3. 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.
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. 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. Rapid mineralization of alfalfa shoot tissues, together with enhanced water flow by alfalfa RIMs, present a high risk of groundwater contamination.

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. 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 recolonization of alfalfa RIMs interacted with the temporal release of $NO_3$-N by decomposing alfalfa roots, placing the new corn roots in nitrate-enriched environments.

References


Keywords: alfalfa, corn, roots, nitrate leaching, hydraulic conductivity, macropores, root recolonization.
Mots Clés: luzerne, maïs, racines, lessivage, azote, conductivité hydraulique, macropores, recolonisation racinaire