Renewable Agriculture and Food Systems: 21(3); 165–173 DOI: 10.1079/RAF2005139

Effects of green manure use on sweet corn root length density under reduced tillage conditions

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Accepted 3 August 2005 **Research Paper**

Abstract

A green manure (GM) is a crop grown primarily as a nutrient source and soil amendment for subsequent crops. In environments such as Florida, combined use of GM and reduced tillage may improve soil water and nutrient retention and reduce potential groundwater pollution. In the first 3 years of a long-term experiment, use of GM in a reduced-tillage system on a sandy Florida soil benefited the season-long growth of sweet corn (*Zea mays* L. var. Rugosa) much more than final ear yields. To help understand these patterns, we evaluated response of sweet corn roots when in rotation with GM of sunn hemp (*Crotalaria juncea* L.; summer) and cahaba white vetch (*Vicia sativa* L.; winter 2002–2003) and a multi-species mixture of hairy vetch (*V. villosa* Roth.) and cereal rye (*Secale cereale* L.; winter 2003–2004). Treatments included sweet corn with combinations of 0 or 133 kg chemical N ha^{-1} (as NH_4NO_3) and with or without GM. A highly fertilized treatment (267 kg chemical N ha^{-1}) without GM was also included. Soil cores were sampled from three depths (0–15, 15–30 and 30–60 cm) both between and within corn rows. Data from two experiments showed that use of GM increased sampled corn root length density (RLD) by 44–54%, although only within the upper 15 cm of soil in one of the two experiments. Corn following GM plus 133 kg chemical N ha^{-1} produced up to 44% greater RLD than corn with 267 kg chemical N ha^{-1}. Sampled RLD decreased with distance away from corn plants (from in-row to between-row positions, and from shallow to deeper depth), with roughly 85–95% of sampled RLD existing in the top 30 cm of soil across all treatments. During the 2004 experiment, we found that broadcast, as opposed to banded (placed along corn row only), chemical N application resulted in more even distribution of corn RLD between in-row and between-row positions during late-season without regard to GM crop. Although GM permitted optimal sweet corn growth with a 50% reduction in chemical N application, ear fill during the final 1–2 weeks before harvest may have been reduced in GM treatments. GM effects on the amount and spatial distribution of sweet corn RLD may help explain these trends. Provision of greater N from GM residues and/or altered distribution of supplementary chemical N and irrigation may be required to achieve greater ear yield benefit from GM.

Key words: green manure, root length density, sweet corn, reduced tillage, organic amendments, root distribution

Introduction and Literature Review

Due to coarse-textured soil and high temperatures and rainfall, many Florida soils contain little organic matter (less than 10 g kg^{-1}) and have poor water and nutrient retention[1]. Concern exists over potential groundwater nitrate pollution from Florida agricultural systems[2], especially for crops such as sweet corn for which high rates of nitrogen (N) fertilizer are recommended[3].

Legumes utilized as green manure (GM) may provide on-farm sources of organic N. Reduced tillage may also be desirable to slow decomposition of GM residues and increase soil organic matter levels over the long-term in the Florida environment[4]. A long-term study of such reduced tillage, GM-based cropping systems was initiated at UF's Plant Science Research and Education Unit in 2001. However, while short-term effects of GM permitted optimal sweet corn growth with a 50% reduction in chemical N application, ear fill during the final 1–2 weeks before harvest may have been reduced in GM treatments[5]. If patterns in root growth and distribution are associated with these trends, key changes in water and nutrient management may better enable sweet corn producers to transition to reduced-tillage, GM-based systems. However, very little data exist for root behavior of sweet corn under such conditions.

Root length density (RLD)—defined as length of roots per unit volume of soil—may give some indication of plant response to environmental factors[6]. Increased RLD in response to increased nutrient and water availability, a phenomenon known as *root proliferation*, may reflect greater water and nutrient uptake potential[7]. However, root water and nutrient uptake may be dictated by a complex interplay of RLD, soil water and nutrient availability, root age, plant stress and soil aeration status[6,8]. Additionally, soil water and nutrient status may change more rapidly (hours to days) than RLD can respond (days to weeks). Effective rooting depth may limit plant access to water and nutrients as they move down the soil profile. Working with conventional tillage on a silty clay loam in Nebraska, Eghball and Maranville[9] found that a deeply rooted (to 0.9 m) field corn (*Zea mays* var. L) had a greater yield response than shallow-rooted varieties when irrigation led to deeper water infiltration, and that moderate N and water stress increased RLD uniformly throughout the soil profile while severe water and N stress reduced RLD. In a greenhouse study with a potting soil and sand mixture, Eghball et al.[10] removed entire corn root systems and found 52.7, 37.6 and 9.7% of root length in the 0–0.3, 0.3–0.6 and 0.6–0.9 m depths.

Due to different nutrient release characteristics and effects on soil water, temperature, and biota, root growth patterns may be markedly different following GM compared to chemical fertilizer. Because their N release is driven by decomposition, GM may represent a source of slow-release N. Spatial distribution of GM residue may be heterogeneous, creating localized areas of N release and other GM-mediated impacts[11]. GMs may have effects on soil moisture transfers, temperature and populations of root-parasitizing organisms such as nematodes[12,13] which could also affect root growth. To help explain higher ear yields from corn in rotation with GM and supplemented with animal manure compared to monocropped corn with conventional inputs, Goldstein[14] studied field corn roots on a fine-textured soil in Wisconsin under conventional tillage. In this study, corn following GM and animal manure maintained healthier roots. Pallant et al.[15] found greater RLD in the upper 30 cm of soil for corn in rotation with GM. According to Nickel et al.[16], RLD for corn grown in rotation with soybean (*Glycine max*) tends to be higher than that for corn grown in monoculture even with high input use. In a conventional tillage system, Nickel et al.[16] found greater RLD for monoculture corn in shallow soil depths (upper 12.5 cm) during early season while corn in rotation with soybean showed greater RLD in deeper soil layers (between 12.5 and 50 cm) during mid- to late-season. Pallant et al.[15] also found that increases in soil organic matter significantly increased corn RLD on two of four sample dates.

For potato (*Solanum tuberosum* L.), Opena and Porter[17] report that organic amendments (compost plus beef cattle manure) significantly increased RLD in the 0–30 cm plow layer and did not change relative distribution of roots by depth (~85% of RLD in 0–30 cm layer). However, Thorup-Kristensen and van der Boogaard[18] found that surface applying increased amounts of high-N GM residue reduced carrot (*Daucus carota* L.) root proliferation in the upper 1 m of soil and shifted roots closer to the plant.

We investigated a GM-based rotation of summer planted sunn hemp (SH) followed by a winter legume (L) of blue lupin (*Lupinus angustifolius* L., winter 2001–2002), cahaba white vetch (winter 2002–2003), and a hairy vetch plus rye mixture (winter 2003–2004) as an N source for sweet corn under reduced tillage. In these studies, use of summer plus winter GM produced a cumulative 12–15 Mg dry matter ha^{-1} and up to 240 kg N ha^{-1} annually. Details of GM growth and decomposition patterns are discussed by Cherr[5], as are yield responses of sweet corn to the GM sequence and to the component GM crops alone (summer GM only and winter GM only). To better explain growth and final ear yield patterns for corn with GM, we conducted two root studies of selected treatments. In both experiments, we hypothesized that use of summer plus winter GM would increase overall sweet corn RLD, that sweet corn RLD would be redistributed nearer to the GM residue (in this case, near the surface as we used reduced tillage), and that corn with a high chemical N rate (267 kg NH_4NO_3-N ha^{-1}) would show greater RLD than corn at lower N rates (0 or 133 kg NH_4NO_3-N ha^{-1}) with or without GM. In the 2004 experiment, we also evaluated the effect of chemical N application method on root length distribution, hypothesizing that broadcast application would lead to more even distribution of roots than banded application.

Materials and Methods

Overall set-up and design

Research was conducted at the Plant Science Research and Education Unit near Citra, Florida (University of Florida, Gainesville). Candler fine sand (Typic Quarzipsamments, hyperthermic, uncoated) and Lake fine sand (Typic Quarzipsamments, hyperthermic, coated) were the dominant soil types (typically, both are >95% sand in upper 1–2 m of soil; see reference [1]). The field had been planted with peanut (*Arachis hypogea* L.) 1 year earlier, but previously had remained in long-term grass pasture. The overall project consisted of 15 treatments repeated four times in a randomized complete block design. A complete description of treatments and timeline of events is provided elsewhere[5]. After initial field roto-tilling in 2002, all crops were planted with zero or reduced tillage.

2003 Experiment

Root growth analysis utilized five treatments. GM treatments consisted of sweet corn (spring 2002 and 2003) in

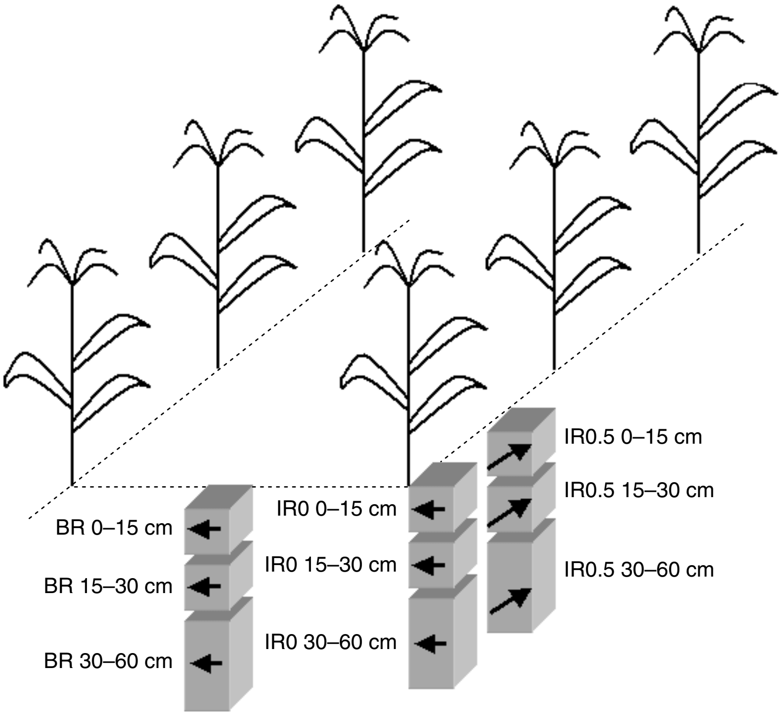

Figure 1. Name, location and relative volume of root core samples in the 2003 experiment (arrows indicate name). Sampling in the 2004 experiment was identical except no cores were taken from IR0.5 at any depth.

rotation with a GM sequence of SH (summer 2001 and 2002), blue lupin (winter 2001–2002), and Cahaba white vetch (winter 2002–2003), with 0 or 133 kg inorganic N ha^{-1} applied to corn (GM 0N and GM 133N, respectively). Conventional treatments consisted of sweet corn with 0, 133, or 267 kg inorganic N ha^{-1} applied (Conv 0N, Conv 133N, Conv 267N). Details of GM planting, growth and management are provided elsewhere[5]. In GM 133N, dry matter additions from all crop and weed residues (including corn stover) during the first 2 years of the study averaged roughly 20 Mg ha^{-1} yr^{-1}. During the same period, dry matter additions in Conv 133N and Conv 267N both averaged roughly 9 Mg ha^{-1} yr^{-1}. Residues were mown prior to corn planting and after corn harvest. In both 2002 and 2003, sweet corn (variety GS 0966; Syngenta; Basel, Switzerland) was planted in April with in-row spacing of 18 cm and between-row spacing of 75 cm. In 2003, corn emerged on April 15, 2003. All chemical N was applied as NH_4NO_3 in three equal split applications at 0, 3 and 5 weeks after emergence (WAE). Chemical N was band applied to corn rows by hand. Samplings of these treatments for RLD analysis in the 2003 experiment took place during the second year of sweet corn (2003).

Using a 5-cm soil auger (Forestry Suppliers, Inc; Jackson, MS) of known volume, soil cores were extracted at 3, 5 and 8 WAE of sweet corn. In each plot, soil was extracted from three different depths: 0–15; 15–30 and 30–60 cm; and in three different surface positions: in-row and immediately adjacent to a corn plant (IR0); in-row and halfway between two corn plants (IR0.5); and between-row (halfway between two corn rows; BR), giving nine unique locations (Fig. 1). Soil extraction was conducted away from border areas and near plants representative of the plot in both size and spacing. Soil cores were washed in a grain sieve with pores 4.5 mm in diameter. Although root hairs could not be accounted for, this grain sieve satisfactorily retained visible roots which were then separated from debris. RLD for each core was then determined with Winrhizo (Regent Instruments; Quebec City, Canada) software and hardware. Results were transferred to MS Excel (Microsoft Corporation, Los Angeles, CA) for organization and graphical analysis.

To test the effects of GM amendment and chemical N rate on root length and distribution, a balanced ANOVA was run for sample results from GM 0N, GM 133N, Conv 0N and Conv 133N using SAS software package (Statistical Analysis Systems; Cary, NC). Sample RLDs were log transformed by $\log_{10}(x+1)$ before ANOVA to maintain homoscedasticity. RLD was modeled as a function of sample date, N rate, GM use, depth, position, all possible interactions of these main effects and block. Where interaction terms were significant ($\alpha = 0.05$), separate ANOVAs were run to compare levels of one interacting variable within specific levels of the other interacting variable(s). Non-interacting variables (except block) were not included in the interaction model statements. Comparisons of means were always made with Duncan's multiple range test. A similar ANOVA was also conducted with sample data expressed on a relative basis (as a fraction of the total root length sampled from the plot on the corresponding date), permitting comparisons of root distribution between treatments regardless of absolute size. However, because trends were similar to that on a density basis, results of an ANOVA on relative root length basis are not shown.

To compare root length and distribution patterns of these treatments to high-fertilized, high-producing corn, pairwise contrasts of Conv 267N were made with each of the other treatments. A complete ANOVA was conducted on RLD as a function of treatment (all treatments, including Conv 267N), sample date, position, depth, all interactions of these main effects and block. Analyses of significant interactions were identical to that described above.

Transducing tensiometers (model 'R' irrometers; Spectrum Technologies; Plainfield, IL) were installed in selected plots along with suction lysimeters to monitor N leaching. Although suction lysimeters yielded no information, data from transducing tensiometers buried at 15, 60 and 90 cm in GM 133N and Conv 200N are reported here. Data from tensiometers were recorded continuously by Watchdog dataloggers (Spectrum Technologies; Plainfield, IL). Treatment Conv 200N was not sampled for root cores.

2004 Experiment

Based on results of the 2003 experiment, a second study was conducted at the same field site in 2004 using three treatments: GM 133N, Conv 133N and Conv 267N. Crop rotation remained similar to previous years, with SH GM planted in summer 2003, a winter GM of hairy vetch plus rye mixture in winter 2003–2004, and sweet corn (same variety as in 2003) planted in spring 2004 using identical equipment and spacing as in previous years. Combined GM and weed production in GM 133N amounted to roughly 17 Mg ha^{-1} (Avila, 2004, unpublished data). Based on previous years' results, chemical N was distributed at 20% at 0 WAE, and 40% at 5 and 8 WAE each. Root cores were extracted at 4, 6 and 9 WAE from two surface positions: IR, halfway between plants and BR, halfway between plants. Otherwise, field and laboratory procedures were identical to the 2003 experiment.

ANOVA was conducted similar to that involving all treatments in the 2003 experiment. Pairwise contrasts between sampled treatments were made again in the 2004 experiment to evaluate GM effects on corn RLD (GM 133N versus Conv 133N) and compare GM 133N and Conv 133N to highly fertilized corn (Conv 267N). To evaluate effects on RLD and distribution of broadcasting, as compared to banding, of chemical fertilizer, chemical N was broadcast applied in sub-plot sections of 8.4 m^2 in GM 133N and Conv 133N treatments. In main plots, chemical N was applied identically as in the 2003 experiment (banded). Samples from broadcast sub-plots were taken at 9 WAE only. RLD data from these sub-plots, and from (banded) main plots of GM 133N and Conv 133N at 9 WAE were modeled as a function of GM level, N application method, position, depth, all interactions of these main effects and block.

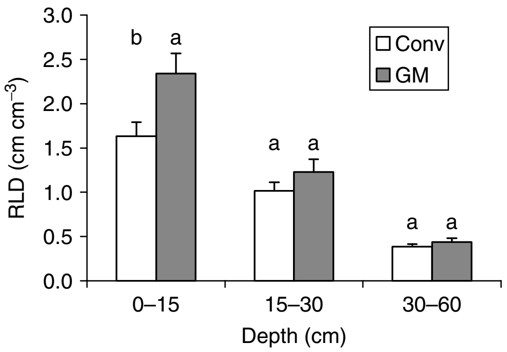

Figure 2. Effect of green manure (GM) and conventional (Conv) treatments on sampled sweet corn RLD by depth over all sampled positions and dates in the 2003 experiment. Error bars reflect standard errors; lower case letters reflect ANOVA differences within sample depth, $P \leqslant 0.05$.

Results

2003 Experiment

RLD and relative root length distribution. Over the season, RLD for the sampled volume in the upper 0–60 cm soil layer remained within one order of magnitude in all treatments, from 0.17 to 1.65 cm cm^{-3}, consistent with other studies[14–16]. Use of GM increased corn RLD in the upper (0–15 cm) soil layer by 44%, with smaller increases in deeper layers (15–30 and 30–60 cm) that were non-significant (Fig. 2). A three-way interaction between sample date, chemical N rate and GM level (Table 1; sub-effects not shown) showed that GM use increased RLD throughout the entire 0–60 cm soil layer only during late-season when no N (0N) was applied (data not shown). Moreover, conventional corn showed greater RLD response to chemical N during late-season growth than GM amended corn (data not shown).

Across all positions or depths, corn RLD increased significantly only from 3 to 5 WAE. Exception to this occurred at 30–60 cm depth, where increase continued from 5 to 8 WAE. Additionally, RLD increase in the BR position from 3 to 5 WAE appeared less than in either IR position (Table 2). RLD decreased from IRs (IR0, IR0.5) to BR positions but did not differ between IR0 and IR0.5 positions. In the BR position, RLD at 15–30 and 30–60 cm depths were quite low and did not differ significantly from each other (Table 2). Increasing chemical N rate from 0 to 133 kg N ha^{-1} significantly increased RLD throughout the IR, but not BR, positions, perhaps due to the banded application of N. Across all depths, this increase of chemical N rate increased corn RLD, although increase in the 30–60 cm layer was smallest and may have become significant only when the individual (sub-effect) ANOVA was run (Table 2).

Statistical patterns of relative root length distribution were similar to those of absolute RLD. For all treatments throughout the season, relative root length sampled remained numerically greatest in the IR0 0–15 cm location

Table 1. Significance of GM, N rate, date, position, depth and sub-effects when constituting linear model for sampled RLD in the 2003 experiment.

Model term	Probability (*P*)
Main effects	
Date	< 0.0001
Pos	< 0.0001
Depth	< 0.0001
N rate	< 0.0001
GM	< 0.0001
Two-way interactions	
Date × Pos	< 0.0001[1]
Date × Depth	< 0.0001[1]
Pos × Depth	< 0.0001[1]
Date × N rate	< 0.0001
N rate × Pos	0.0001[1]
N rate × Depth	< 0.0001[1]
Date × GM	NS
GM × Pos	NS
GM × Depth	0.0007[2]
N rate × GM	NS
Three-way interactions	
Date × Pos × Depth	NS
Date × N rate × Pos	NS
Date × N rate × Depth	NS
N rate × Pos × Depth	NS
Date × GM × Pos	NS
Date × GM × Depth	NS
GM × Pos × Depth	NS
Date × N rate × GM	0.0137[3]
N rate × GM × Pos	NS
N rate × GM × Depth	NS
Four-way interactions	
Date × N rate × Pos × Depth	NS
Date × GM × Pos × Depth	NS
Date × N rate × GM × Pos	NS
Date × N rate × GM × Depth	NS
N rate × GM × Pos × Depth	NS
Five-way interaction	
Date × N rate × GM × Pos × Depth	NS

Pos, position; N rate, chemical N application level; GM, GM level; NS, not significant at the $P \leqslant 0.05$ level.

[1] See Table 2.

[2] See Figure 2.

[3] Not shown (see text).

(23–27%), roughly half or more (up to 55%) of sampled root length was always in the 0–15 cm layer, with the upper 30 cm containing roughly 85% of sampled root length (data not shown). These results are similar to the findings reported by Eghball et al.[10] RLD decreased exponentially with increasing depth from the surface in nearly all plots in all sample dates.

Although ANOVA of all sampled treatments (including Conv 267N) indicated significant two-way interactions of treatment with date, position and depth, pairwise contrasts showed that Conv 267N differed significantly only from Conv 0N and GM 0N for a limited number of sub-effects. Neither Conv 133N nor GM 133N differed significantly from Conv 267N in any pairwise contrast, although RLD for GM 133N was greater than Conv 267N by 22% in the upper 15 cm of soil (data not shown).

Soil water potential. Soil water potential for GM 133N and Conv 200N at 15 cm showed two distinct phases. From 17 April until 20 May (about 0–5 WAE), soil water potential under GM 133N remained significantly higher than Conv 200N by an average of 2.6 ± 0.2 kPa (Fig. 3A). Average soil water potentials at 15 cm during this period were −16.5 ± 0.4 kPa for GM 133N and −19.1 ± 0.5 kPa for Conv 200N. Greatest differences occurred during the 12-day period from 19 April to 1 May when soil water potential under GM 133N was 3.9 ± 0.1 kPa higher than under Conv 200N. From 21 May until final harvest on 19 June (about 5–9 WAE) this trend reversed, with soil water potential under Conv 200N (−13.7 ± 0.2 kPa) becoming significantly higher than in GM 133N (−14.9 ± 0.1 kPa) by an average of 1.2 ± 0.2 kPa. Overall, average daily soil water potential for both treatments increased logarithmically over the season, probably reflecting greater water potential near the surface after canopy closure and shading (Fig. 3A).

Soil water potential at 60 cm also underwent two distinct phases but with an intermediate 'transition' period during which water potential in both GM 133N and Conv 200N was relatively equal (Fig. 3B). From 17 April to 5 May (about 0–3 WAE) soil water potential at 60 cm remained lower in GM 133N (−15.1 ± 0.5 kPa) compared to Conv 200N (−13.9 ± 0.3 kPa) by an average of 1.2 ± 0.3 kPa. Soil water potential for the two treatments at 60 cm was not significantly different from 6 May to 25 May (about 3–6 WAE), but from 26 May to final harvest (about 6–9 WAE) tensiometer readings showed higher soil water potential for GM 133N (−11.8 ± 0.4 kPa) compared to Conv 200N (−13.8 ± 0.5 kPa) by an average of 2.0 ± 0.2 kPa. Tensiometer readings from 90 cm showed lower soil water potential throughout the season for GM 133N (−10.2 ± 0.4 kPa) compared to Conv 200N (−8.8 ± 0.3 kPa) by an average of 1.4 ± 0.3 kPa (data not shown).

2004 Experiment

RLD and relative root length distribution. Because sample dates and timing of N fertilization differed, results from the 2004 experiment cannot be compared statistically to the 2003 experiment. However, across all sample dates (4, 6 and 9 WAE) and treatments (GM 133N, Conv 133N and Conv 267N) within the 2004 experiment, the range of RLD in the upper 0–60 cm soil layer remained between 0.13 and 1.64 cm cm^{-3}, similar to the range found in the 2003 experiment. Use of GM again increased corn RLD by 54%. Unlike results from 2003, this increase occurred throughout the upper 60 cm of soil (Table 3). Also unlike the 2003 experiment, pairwise contrasts showed GM 133N to have significantly higher

Table 2. RLD (cm cm^{-3}) by interactions between position and date, position and depth, position and N rate, depth and date, and depth and N rate in the 2003 experiment.

	Position				Depth		
Date	**IR0**	**IR0.5**	**BR**	**Date**	**15 cm**	**30 cm**	**60 cm**
3WAE	0.37Ba	0.36Ba	0.22Bb	3WAE	0.69Ba	0.54Bb	0.24Cc
5WAE	1.07Aa	0.91Aa	0.47Ab	5WAE	2.43Aa	1.33Ab	0.44Bc
8WAE	1.25Aa	1.00Aa	0.49Ab	8WAE	2.83Aa	1.50Ab	0.55Ac
Depth				**N rate**			
15 cm	2.63Aa	2.08Aa	1.25Ab	0N	1.34Ba	0.87Bb	0.33Bc
30 cm	1.51Ba	1.45Ba	0.41Bb	133N	2.63Aa	1.38Ab	0.49Ac
60 cm	0.51Ca	0.45Ca	0.27Bb				
N rate							
0N	1.11Ba	0.99Ba	0.59Ab				
133N	2.07Aa	1.84Aa	0.89Ab				

N, kg chemical N ha^{-1}. Means within rows having same lower case letters and means within columns having same capitalized letter do not differ at the $P \leqslant 0.05$ level according to Duncan's multiple range test.

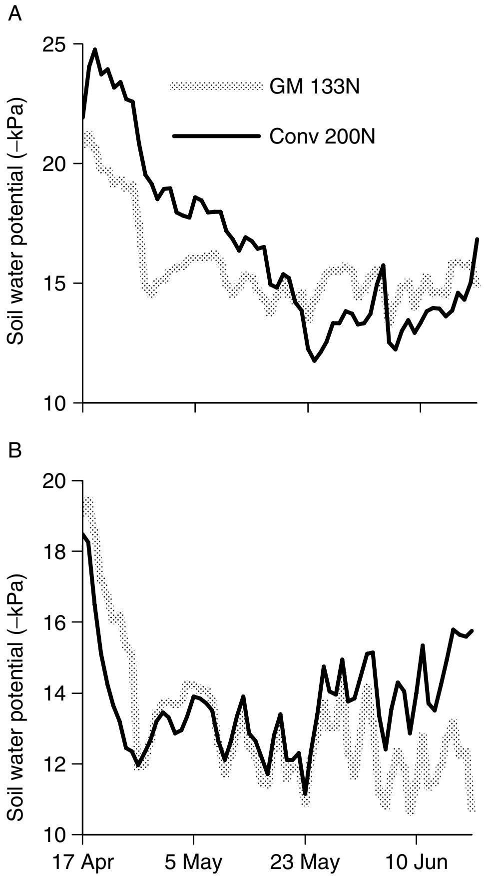

Figure 3. Soil water potential at 15 cm (A) and 60 cm (B) during sweet corn growth in the 2003 experiment. Data are shown for sweet corn following GM and fertilized with 133 kg chemical N ha^{-1} (GM 133N) and sweet corn fertilized with 200 kg chemical N ha^{-1} only (Conv 200N).

RLD than Conv 267N (by 44%) throughout the upper 60 cm of soil (Table 3).

Although full ANOVA indicated significant interactions for position × date and position × depth (Table 3), sub-effects were non-significant (Table 4). RLD appeared relatively unaffected by date, probably due to later initial sampling (4 WAE) than in the 2003 experiment. RLD increased when moving from BR to either IR position during any sample date and increased from lower to higher depth without apparent interaction with position (Table 4).

Corn RLD distribution was qualitatively similar to that found in the 2003 experiment. Roughly 75% of sampled RLD existed in the IR position, and about 95% of sampled RLD existing in the upper 30 cm. However, at final sampling (9 WAE, coinciding with maturity), corn in sub-plots with broadcast application of 133 kg N ha^{-1} showed more even distribution of roots than corn with banded N when comparing RLD for BR and IR positions (Fig. 4). BR RLD in banded treatments amounted to only 26% of total sampled RLD, while in broadcast treatments this proportion increased to 41%. However, pairwise contrasts of corn RLD between broadcast and banded treatments showed no significant differences, nor did GM application, position and depth have interactive effect with the method of N application on corn root RLD at this date. As in the 2003 experiment, representation of data as relative root lengths did not qualitatively alter statistical results, indicating that absolute trends in RLD did not mask changes in relative root distributions.

Discussion

Despite variability inherent in root core work, we resolved definite patterns of corn root distribution within the study environment. These patterns help explain corn growth and yield performance as found by Cherr[5] and Avila (2004, unpublished). Including weeds and stover from corn crops, use of a productive GM system contributed about 20 Mg residue ha^{-1} yr^{-1}, roughly 10–12 Mg ha^{-1} yr^{-1} more than the conventional approach. About half of this residue was

Table 3. Significance of treatment, date, position, depth and sub-effects when constituting linear model for sampled RLD in the 2004 experiment.

Model term	Probability (*P*)
Main effects	
Date	0.0002
Pos	< 0.0001
Depth	< 0.0001
Trt	< 0.0001
GM 133N	1.09a
Conv 133N	0.71b
Conv 267N	0.76b
Two-way interactions	
Date × Pos	0.0189[1]
Date × Depth	NS
Pos × Depth	< 0.0001[1]
Date × Trt	NS
Pos × Trt	NS
Depth × Trt	NS
Three-way interactions	
Date × Pos × Depth	NS
Date × Pos × Trt	NS
Date × Depth × Trt	NS
Pos × Depth × Trt	NS
Four-way interaction	
Date × Pos × Depth × Trt	NS

Trt, treatment; Pos, position; N, kg chemical N ha^{-1}; NS, not significant at the $P \leqslant 0.05$ level.

[1] See Table 4.

Table 4. Effects of interactions between position and date or depth on RLD (cm cm^{-3}) in the 2004 experiment.

	Position	
Date	**IR**	**BR**
4WAE	0.85Aa	0.42Ab
6WAE	1.50Aa	0.43Ab
9WAE	1.46Aa	0.48Ab
Depth		
0–15 cm	3.15Aa	1.16Ab
15–30 cm	1.36Ba	0.44Bb
30–60 cm	0.29Ca	0.09Cb

Means having same letters do not differ at the $P \leqslant 0.05$ level according to pairwise contrast.

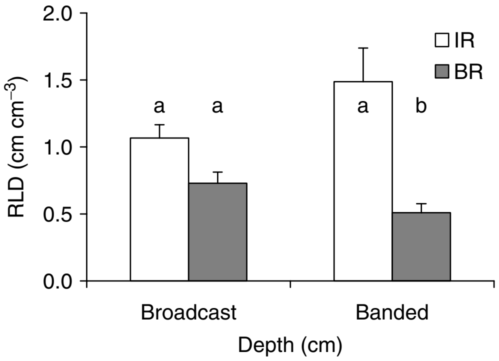

Figure 4. Effect of chemical N application method on sampled sweet corn RLD by position in the 2004 experiment. Error bars reflect standard errors; lower case letters reflect ANOVA differences within application method, $P \leqslant 0.05$.

highly recalcitrant stem material from SH. After 2–3 years in a reduced-tillage system on sandy soil, these GM additions increased sweet corn RLD by 44–54%, although in the 2003 experiment doing so only in the upper 15 cm of soil.

In the 2003 experiment, GM amendment benefited corn RLD throughout the upper 60 cm of soil and at late-season (1 week before harvest) only without chemical N (GM 0N). Increased root proliferation near the soil surface may have occurred if GM residue slowed the movement of chemical N fertilizer through immobilization and subsequent re-mineralization. In the 2004 experiment, differences in scheduling of chemical N application to corn and accumulation of organic matter from an additional year of GM growth may have distributed the significantly positive RLD response to GM more evenly throughout the upper 60 cm. However, increased sample variability, fewer samples, and later sample dates may have also masked finer differences between depths.

Although corn with 267 kg N ha^{-1} received roughly 40 kg N ha^{-1} more than corn in GM 133N treatments (when considering both GM residues present at the time of corn planting and chemical N applied to corn), corn with GM 133N maintained RLD up to 44% greater than Conv 267N. Detailed growth analysis for corn from the 2003 experiment revealed that GM 133N performed similarly to Conv 267N throughout the growing season in terms of tissue dry weights and leaf indicators[5]. Tensiometer data from the 2003 experiment reveals that surface residue may also have created an environment of greater water availability at 15 cm below the soil surface, especially early in the season before canopy closure (Fig. 3A). Coupled with possible net N release from decomposition, root proliferation near the soil surface may have benefited plants during early-season. Only during the final week before maturity did total plant N mass and ear dry weight for Conv 267N become significantly greater than that of GM 133N. By late-season, the moisture level at 15 cm depth in GM 133N treatments dropped below that of conventionally fertilized corn of similar biomass. Root proliferation above 15 cm may therefore have exposed plants to water stress during ear fill, although it should be noted that water potential at 15 cm in both treatments rose over time (probably due to shading from canopy closure). Higher late-season water potential at 60 cm in GM 133N plots (compared to conventional) also suggests that corn in this treatment took up less water at lower depths during late-season compared to conventionally fertilized corn of similar biomass (Fig. 3B).

Growth analysis from the 2003 experiment also demonstrated significant late-season uptake of N by sweet corn[5]. Corn in Conv 267N treatments, receiving roughly 40 kg total N ha^{-1} more than GM 133N (including both residue and chemical N sources), may have benefited from late-season uptake of this ‘additional’ N. Root proliferation near GM residue on the soil surface may have allowed corn in GM 133N treatments to remain competitive if there was an increased water and/or higher N release beneath residue despite lower chemical N rate, especially during early and mid season. Similar root distribution effects were reported by Thorup-Kristensen and van der Boogard[18] for carrot amended with large amounts of surface-applied GM. These results complement and contrast findings under conventional tillage, where GM use also appears to increase overall RLD but at lower soil depths[16,17], while chemical approaches to N fertilization may encourage root proliferation near the soil surface[15].

In the 2003 experiment, GM amendment benefited corn RLD throughout the upper 60 cm of soil and at late-season (1 week before harvest) only in the absence of chemical N fertilizer. More uniform RLD response to GM from unfertilized corn (compared to fertilized corn) may have been related to more uniform availability of soil N underneath recalcitrant SH residue when chemical N was not applied. Attempts to quantify soil solution N levels using suction lysimeters were unsuccessful. More uniform increase of RLD with GM use might be desirable if it increased overall N and/or water uptake. However, corn in GM 0N treatments achieved only 46 and 3% of dry weight and marketable ear yields, respectively, produced by Conv 267N during the 2003 season. Therefore, such an approach to sweet corn production is not practical in our environment.

Providing GM with N content closer to that applied with chemical fertilizer must remain a priority. However, it is unclear if shallow-root proliferation beneath GM residue resulted in a net disadvantage for sweet corn growth. Soil incorporation of GM residue to help encourage deeper root growth under these circumstances might be favorable if subsequent nutrient loss from decomposition did not negate the benefits. However, in warm humid areas with coarse-textured soil, reduced tillage is often desired to slow organic matter decomposition and nutrient loss and improve soil water retention[19–22]. In such reduced-tillage systems, improved use of GM may necessitate different irrigation managements, including drip lines buried below surface residue and/or use of small, frequent irrigations during the late-season. Use of individual GM species or GM mixtures with more substantial below ground production (e.g., tuber crops) may also create a better rooting environment at deeper depths, and may also be important for increasing N retention[5].

Generally, maximum sweet corn RLD was achieved by 4–5 WAE in all treatments in both experiments. Significantly, more corn RLD existed near the soil surface and at IR positions (relative to BR positions), and RLD increase over time appeared slower in the BR position (both absolutely and as proportion of pre-existing roots). In the 2004 experiment, however, broadcast application of N resulted in more even distribution of corn roots between IR and BR positions near maturity. Coelho and Or[23] showed that for corn a relatively minor fraction of total RLD located BRs can make disproportionately large contributions to root water uptake when water becomes more available there than closer to the plant. However, increases in the effective N contributions from GM probably must accompany improvements in corn root distribution, and root uptake potential must match the timing and location of N and water availability.

Conclusions

Use of GM may alter root distribution patterns of subsequent crops, possibly with effects on production. In a reduced-tillage system on sandy soil with band applied chemical N, GM increased sweet corn RLD, but one of the two experiments did so only in the upper 15 cm of soil. Despite receiving up to 40 kg total N ha^{-1} less (including organic and inorganic sources), corn in rotation with GM plus 133 kg inorganic N ha^{-1} maintained RLD equal to or greater than corn with 267 kg inorganic N ha^{-1} in both experiments. Increased water and/or N availability in the upper soil depth during early-season may have given corn following GM an advantage at this time, but by late-season lack of N and/or water in this layer may have reduced ear-fill.

Most sweet corn root length appeared to exist within 30 cm of the soil surface and to occur near the plant. Water and nutrients well below this depth and/or in between row areas may become relatively unavailable for these plants. Broadcast application of chemical N may encourage more even distribution of root growth throughout the plot, but it remains unclear if this root growth occurs in the proper amount and timing to take up N in the between row area.

Acknowledgements. Supported by grant number LS02-140, Sustainable Agriculture Research and Education, United States Department of Agriculture; and by the Center for Cooperative Agricultural Programs, Florida Agricultural and Mechanical University and University of Florida.

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