Uptake of Point Source Depleted ^{15}N Fertilizer by Neighboring Corn Plants

P. J. Hodgen, R. B. Ferguson, J. F. Shanahan, and J. S. Schepers*

ABSTRACT

Ground-based active (self-illuminating) sensors make it possible to collect canopy data that are useful for making on-the-go N fertilizer application decisions. These technologies raise questions about plant-to-plant competition for targeted fertilizer N applications. This study evaluated the extent to which fertilizer N applied to an individual corn (*Zea mays* L.) plant might be intercepted by adjacent plants in the row. Depleted ^{15}N ammonium-nitrate was injected under the center maize plant while the four neighboring plants on each side in the row received the same rate as natural abundance ammonium-nitrate fertilizer. Aboveground biomass was collected 10 (at V12) and 7 (at R1) d after each fertilizer application. Plants were separated into three components at each sampling date. The uptake pattern of depleted ^{15}N indicated an individual maize plant acquires most of its in-season N from an area within a ~40-cm radius. Adjacent plants ~18-cm away from the tagged-N source contained 32 to 40% of the total depleted ^{15}N that was taken up by all nine plants in the sequence. Maize plants ~36 cm from the point source only acquired 5 to 13% of the depleted ^{15}N source that was taken up by all nine plants. It is presently impractical to position in-season by-plant N applications beneath plants as done in this study. Surface applications of liquid N near target plants is presently possible, but the relative effectiveness would likely be less than for injection of the fertilizer beneath each plant.

ESTIMATES OF nitrogen use efficiency (NUE) in corn cropping systems are only 37% (Cassman et al., 2002) and 33% (Raun and Johnson, 1999) for cereal crops grown worldwide. Recently developed active sensor technologies (GreenSeeker, Ntech Industries, Inc., Ukiah, CA; Crop Circle, Holland Scientific Inc., Lincoln, NE)[1] are being evaluated as potential tools to guide spatially variable rate applications of N fertilizer to increase NUE. These sensors typically output Normalized Difference Vegetation Index type data 10 times per second (Tucker, 1979), which amounts to every 22 cm along a row at a ground speed of 8 km h^{-1}. Studies involving wheat (*Triticum aestivum* L.) and Bermuda grass [*Cynodon dactylon* (L.) Pers.] show that this resolution may allow the development of fertilizer management schemes that recognize differences in plant densities, biomass production, and yield potential (Martin et al., 2007) at 1-m resolution or less (Raun et al., 2002).

Martin et al. (2005) illustrated that individual plant yield (i.e., grain per plant adjusted for soil area occupied by that plant) from one corn plant to another can vary widely in a linear transect of row. Maddonni and Otegui (2004) reported that hierarchy among individual corn plants is usually established by V6 (Ritchie et al., 1997) and affects the final kernel number of each plant. If N fertilizer could be managed to reflect differences in the ability of corn plants to capture scarce resources (e.g., light, soil moisture, and N) (Maddonni and Otegui, 2006), this could lead to higher NUE in corn cropping systems. However, the possibility exists that the NUE of the target plant could be reduced if neighboring plants intercept some of the targeted N fertilizer.

The amount of N being scavenged away from a target plant would most likely reflect the degree to which roots from neighboring corn plants intermingle in a common volume of soil. Mengel and Barber (1974) found corn root density was greatest in the upper soil surface (0–15 cm) directly under the plant early in the growing season. These and other authors observed that as the season progressed the root density in the upper surface soil generally increased, but decreased with horizontal distance from the plant (Crozier and King, 1993; Mengel and Barber, 1974). Furthermore, the distribution of a corn plant's roots can be influenced by the application rate of N (Durieux et al., 1994), the type of N being supplied (Anghinoni and Barber, 1988; Schortemeyer and Feil, 1996), and the placement of N within the root zone (Anderson, 1987; Gass et al., 1971).

Studies using stable isotopic N fertilizer have been able to trace fertilizer N movement through the soil–plant system for more accurate calculation of fertilizer recoveries and improved accountability through potential loss pathways (Hauck, 1973; Westerman and Kurtz, 1973; Kitur et al., 1984; Reddy and Reddy, 1993). Using fertilizer sources enriched with ^{15}N (>0.367 ^{15}N atom percent; Atm%) can be expensive when applied to large areas as in typical agronomic field plots. Therefore, investigators have sought to determine the minimum

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[1] Mention of commercial products is for the benefit of the reader and does not imply endorsement by USDA-ARS or the University of Nebraska.

Abbreviations: Atm%, atom percent; NUE, nitrogen use efficiency.

size of microplots needed to ensure reliable data are obtained (Johnson and Kurtz, 1974; Jokela and Randall, 1987; Olson, 1980). These studies compared the ^{15}N Atm% enrichment of plants in the center of plots with those obtained at various distances from the borders. Johnson and Kurtz (1974) determined that a row of corn plants, spaced at 0.76 m, acquired its entire N supply from the soil area between the two adjacent rows. Olson (1980) stated that the Johnson and Kurtz (1974) design would only be applicable if N was banded and would not provide reliable residual soil N data for broadcast applications. Olson (1980) reported corn plants spaced more than 0.36-m inside the microplot contained similar levels of labeled N fertilizer as those corn plants in the center of the plot with 2.84-m borders. Olson suggested that a 2.84- by 2.84-m plot would have sufficient size and offer adequate isolation to use the center eight plants (58,700 plants ha^{-1}) from each of the center two rows (0.71-m spacing) for determining N uptake. Further, the furrow area between the two center rows could be used to obtain reliable residual soil N data from a broadcast N application. Jokela and Randall (1987) found similar results to those of Olson (1980) and Johnson and Kurtz (1974), but suggested that a 1.52- by 2.29-m microplot centered lengthwise over the row (0.76–m spacing) would be sufficient for N uptake and residual soil N data. These studies did not track the uptake of N applied to a single corn plant relative to the competition provided by its neighbors. The effectiveness of high spatial resolution, variable rate N management schemes will be influenced by the amount of competition for the targeted N application from neighboring corn plants in the vicinity.

The objective of this work was to determine the N uptake characteristics of neighboring corn plants in response to a point application of depleted ^{15}N fertilizer to a target corn plant.

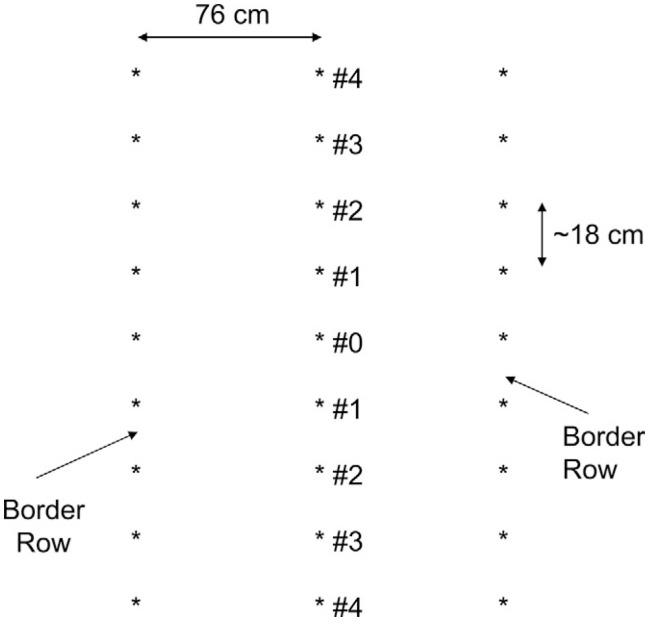

Fig. 1. Plot layout for N fertilizer injection beneath corn plants. Numbers indicate plant position in the row and grouping for lab analysis of vegetative components relative to the target plant (#0).

MATERIALS AND METHODS

The experimental site was located near Shelton, NE (40°45′01″ N, 98°46′01″ W; elevation 620 m above mean sea level), in the Central Platte River Valley. The soil is classified as a Hord silt loam (fine-silty, mixed mesic Pachic Haplustolls) and for the three previous years was uniformly managed in a continuous corn system. Dekalb DKC60–19, which is a 110 d relative maturity Roundup Ready/Yield Guard Corn Borer hybrid (Monsanto Inc., St. Louis, MO), was planted on 19 May, 2005, with a final stand of 73,000 plants ha^{-1}. The site was irrigated as needed with a lateral movement overhead sprinkler system. Tillage at the site involved double-disking before planting with a four-row John Deere 7000 MaxEmerge mounted finger pick up unit. At planting, a starter fertilizer (10–34–0) was applied to the side and below the seed furrow at a rate of 94 L ha^{-1} delivering a rate of 13 kg N ha^{-1}.

The experimental approach was to treat a central plant with depleted ^{15}N fertilizer and treat the neighboring plants with the same amount of commercial N fertilizer. The pattern of depleted ^{15}N accumulation in each plant a few days after in-season N application would be used to assess the extent of plant-to-plant competition and disposition of the depleted ^{15}N within plants. Plots were three rows wide (0.76-m spacing) and approximately 1.6-m long with the center row containing nine evenly spaced corn plants (Fig. 1). The study was considered a complete block design because plots with uniform plant distribution in different rows within a block were identified for N application. A double set of plots in each replication was established to accommodate two application dates that coincided with likely in-season N application times used by producers (i.e., mid-vegetative and early reproductive stages). Nine replications were used on the first treatment date and 10 on the second date. The first point application occurred on 5 July (V9) and the second on 25 July (VT). All depleted ^{15}N fertilizer and plant uptake data were collected from the center row in each plot. The selected sections of row utilized for the second sampling date received a side-dress application of 56 kg N ha^{-1} of ammonium nitrate (34–0–0) at V9. This was done to prevent an N deficiency from occurring before the late season treatment was initiated.

To prepare for the point-source N applications, a well hole was punched into the soil using a common screw driver. A syringe and long needle were used to apply N solution directly under each plant. Each well hole started 15 cm from the plant (perpendicular to the row direction) at a downward 45° angle in the direction of the plant and extended for 21 cm. The goal was for the 10 mL of fertilizer solution to be placed 15-cm beneath each plant without disturbing the roots significantly. Bulk solutions for each N source were prepared by dissolving each in distilled water to achieve a concentration of 0.12 g N mL^{-1}. The appropriate solution (depleted ^{15}N and natural abundance) was then injected into the bottom of the well hole using a dedicated syringe to prevent contamination. The center plant (plant position 0) of each selected row section received 1.2 g of depleted ^{15}N (99.99 Atm%^{14}N) as ammonium nitrate ($^{14}NH_4$ + $^{14}N0_3$). The four neighboring plants (plant positions 1 to 4) on each side of the center plant received 1.2 g of natural abundance N as ammonium nitrate. The first in-season N application (5 July, V9) was followed by ~25 mm water via sprinkler irrigation on 9 July. These plants were sampled on 15 July (V12). The N application scheme was repeated on the second set of plots on 25 July (VT). These plots received ~25-mm irrigation immediately after fertilizer injection and plants were sampled on 1 August (R1). The above approach was somewhat patterned after the effect that Timmons and Baker (1991) achieved with a spoke-injector running near the rows. They injected isotopic N fertilizer at uniform intervals near the row while the above protocol specifically places the individual doses of liquid N fertilizer directly under each plant.

The plant sampling strategy was to separate each plant into components that represent material that developed at different growth stages to trace the fate of the depleted ^{15}N fertilizer. For the first sampling (V12), the upper component consisted of the top collared leaf plus the whorl. The second component represented all of the remaining leaves separated at the collar. The third component represented the stem and leaf sheath material. For the second sampling (R1), all leaves were removed from the stem at the collar to represent the first component. The immature ear, husks, and shank represented the second component. The stem, leaf sheaths, and tassel represented the third component. The collection process for each replication always started with the center plant, which received the depleted ^{15}N fertilizer, and then progressed outward one plant at a time. Vegetative components for each plant were cut in smaller pieces and placed into individually labeled paper bags. The hand clipper was washed with ethanol between each replication.

Samples were placed in a forced air oven at 65°C for 96 h, followed by dry weight determination. Samples were ground with a Wiley mill to pass through a 2-mm screen. The grinding order was the same as the harvest order, with the grinder cleaned with ethanol between each replication. The samples were further ground to pass through a 100-mesh screen with a roller mill grinder as described by Arnold and Schepers (2004). To economize on analytical costs, neighboring plant components from the same relative position from the target plant were combined within a replication.

Total N and carbon content, as well as isotopic composition (δ^{15}N, δ^{13}C) of plant samples (2.8 ± 0.1 mg), were measured by an automated combustion elemental analyzer interfaced with a continuous-flow isotope ratio mass spectrometer (PDZ Europa, Cheshire, UK). Samples were prepared as described by Schepers et al. (1989). Sorghum (*Sorghum bicolor* L.) flour ($\delta^{15}N = 1.58$ ‰, $\delta^{13}C = -13.68$ ‰) was used as the plant working standard. Analytical precision (instrumental error plus sample preparation error) for N isotopic composition was 0.23‰ (SD, $n = 6$) while carbon was 0.39‰ (SD, $n = 6$). Data were analyzed using the Proc Mixed Procedure in SAS (SAS Institute, 2005).

RESULTS

Mid-Vegetative Stage

At the V12 stage, the mean biomass weights of each vegetative component were significantly different from each other when averaged over plant positions (Table 1). The stem contained the most biomass, while the top collared leaf and whorl had the least. There was no significant difference between the mean biomass weights or N concentration between neighboring plants (Table 1). There was also no significant interaction between vegetative component and corn plant position on biomass weights, N concentration, or ^{15}N content.

The average total N concentration over corn plant positions for each vegetative component was significantly different. The average total N concentration was the lowest in the stem (11 g kg^{-1}) and highest in the top leaf plus whorl (25 g kg^{-1}). Inclusion of senescing leaves at the bottom of the plants in the V12 sample could be a plausible explanation for the average N concentration of the bottom leaves being lower than the top leaf and whorl, especially since N is transported to newer leaf material from older leaf material (Bigeriego et al., 1979). The Atm ^{15}N concentrations were the lowest (most depleted ^{15}N uptake) in the plant directly over the depleted ^{15}N source (0.194 Atm%, Table 1) and increased with distance for the first (0.291 Atm% at ~18 cm) and second (0.341 Atm% at ~36 cm) plants away from the depleted ^{15}N source. Plants located ~54 cm from the depleted ^{15}N source contained essentially natural abundance levels of ^{15}N (0.368 Atm% compared to the natural abundance value of 0.367 Atm%).

Data collected at V12 indicate the corn plants were partitioning newly acquired N into developing vegetative components (Table 1). For example, the target plant's (position 0) top collared leaf and whorl contained significantly ($P < 0.05$) lower concentrations of ^{15}N (0.185 Atm%) when compared with the fully developed bottom leaves (0.256 Atm%) but not

Table 1. Analysis of variance of the means of dry weight, N concentration, ^{15}N atom percent (Atm%), and plant distance for each vegetative component across plant positions at V12.

Vegetative component	Plant position from depleted ^{15}N source	Dry weight†	N†	^{15}N	Distance between plants
		g	g kg^{-1}	Atm %	cm
Leaves	0	64 (9)	20 (27)	0.256 m‡	19
	1	65 (8)	24 (14)	0.333 n	18
	2	66 (8)	23 (16)	0.364 n	17
	3	68 (9)	23 (15)	0.375 n	18
	Avg.	66 a§	23 b	0.332 c	
Stems	0	77 (14)	11 (17)	0.130 m	19
	1	78 (6)	11 (17)	0.254 n	18
	2	81(9)	11 (14)	0.322 o	17
	3	84 (13)	10 (13)	0.359 o	18
	Avg.	80 b	11 a	0.269 a	
Top leaf + whorl	0	57 (5)	25 (13)	0.185 m	19
	1	57 (4)	25 (12)	0.286 n	18
	2	57 (4)	24 (14)	0.338 no	17
	3	57 (2)	25 (9)	0.370 o	18
	Avg.	57 c	25 c	0.295 b	
Average over vegetative components	0	66	19.2	0.194 x¶	19
	1	67	20.3	0.291 y	18
	2	68	19.3	0.341 z	17
	3	69	19.2	0.368 z	18
ANOVA					
Source	df		$P > F$		
Plant position (PP)	3	0.1	0.55	<0.0001	
Vegetative component (VC)	2	<0.0001	<0.0001	0.0002	
VC × PP	6	0.59	0.27	0.380	

† Numbers in parentheses are the coefficient of variation (%).

‡ Letters m, n, o indicate significant differences ($P < 0.05$) between means of each plant position within each vegetative component.

§ Letters a, b, c indicate significant differences ($P < 0.05$) between means across plant positions for each vegetative component.

¶ Letters x, y, z indicate significant differences ($P < 0.05$) between means across vegetative components for each plant position.

the developing leaves contained within the stem component (0.130 Atm%) of the sample. This pattern was also observed in the first neighboring corn plants. The target plants and the first neighboring corn plants contained significantly lower concentrations of ^{15}N ($P < 0.05$) in the stem compared with the second and third neighboring corn plants (Table 1). The ^{15}N concentration of stems from corn plants in position two were not significantly lower than stems from corn plants in position three. The vegetative components of corn plants three positions away from the target plant had a ^{15}N concentration near natural abundance.

Total depleted ^{15}N fertilizer uptake was calculated for each vegetative component by first determining the difference between natural abundance (0.367 ^{15}N Atm%) and ^{15}N (Atm%) in the vegetative component. This was then multiplied by the total N concentration in the vegetative components times the biomass produced, respectively. Results indicate the top leaf and whorl of the target plant contained the most depleted ^{15}N fertilizer (Fig. 2). The stem and bottom leaves of the target plant contained significantly more depleted ^{15}N fertilizer than the same vegetative components of the first neighboring corn plants. In addition, the top leaf and whorl of the first neighboring corn plants contained more depleted ^{15}N fertilizer than corn plants two positions away from the target plant. These data indicate corn plants two positions away have partial access to fertilizer placed directly under the target plant. This assessment is further supported by the observation that the amount of depleted ^{15}N fertilizer taken up by plants in position two was not in sufficient quantity to be significantly different from corn plants in position three.

Early Reproductive Stage

At the R1 sampling stage, depleted ^{15}N uptake decreased with distance from the N source as observed at V12 (Table 2). Total tagged N uptake accounted for 3.2 and 1.0% of the tagged N applied under the target plant at V9 and VT, respectively. There was a significant ($P < 0.05$) difference between the mean biomass weights across corn plant positions at the R1 sampling date (Table 2). Yet, these differences are not considered meaningful because the difference between average biomass weights was only 7 g plant^{-1} out of an average of 90 to 97 g plant^{-1}. These small differences in weight could also be attributed to differences in plant spacing or spatial differences in soil N availability. The interaction between plant positions and vegetative components for biomass weights was not significant. The stems had the greatest weight while the immature ear had the least and both were significantly different from the weight of all leaves.

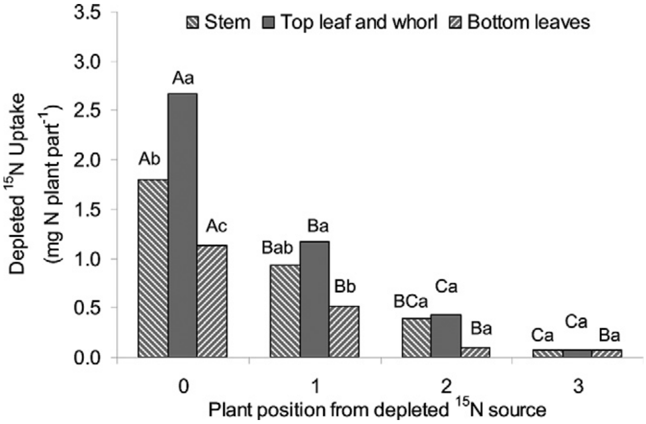

Fig. 2. Depleted ^{15}N uptake at V12 for each plant component at each position relative to the depleted ^{15}N source applied at position #0. Uppercase letters indicate difference ($P < 0.05$) for vegetative components across plant position. Lowercase letters indicate differences ($P < 0.05$) between vegetative components within each plant position.

The average N concentration was not significantly different between corn plant positions at R1 (Table 2). Similar to the observations at V12, the stem contained the lowest (5.5 g kg^{-1}) average total N concentration while the leaves contained the highest (25.1 g kg^{-1}). There was no significant interaction between vegetative components and plant position for total N concentration.

The stem and immature ear components at R1 had significantly lower concentrations of ^{15}N for the target plant and immediate neighboring corn plants compared with the corn plants in positions two and three (Table 2). Furthermore, within the target and first neighboring corn plants, the stem and immature ear contained lower concentrations of ^{15}N (i.e., greater uptake of depleted ^{15}N fertilizer) compared with their leaves. There was no observed difference in the concentration of

Table 2. Analysis of variance of the means of dry weight, N concentration, ^{15}N atom percent (Atm%), and plant distance for each vegetative component across plant positions at R1.

Vegetative component	Plant position from depleted ^{15}N source	Dry weight†	N†	^{15}N	Distance between plants
		g	g kg^{-1}	Atm%	cm
Leaves	0	78 (13)	25.7 (15)	0.336 m‡	16
	1	79 (11)	25.0 (15)	0.364 n	16
	2	82 (9)	25.4 (13)	0.376 n	17
	3	83 (15)	24.4 (10)	0.372 n	18
	Avg.	**81 a§**	**25.1 c**	0.362 b	
Stems	0	104 (13)	5.3 (16)	0.264 m	16
	1	103 (10)	5.5 (14)	0.338 n	16
	2	112 (9)	5.8 (12)	0.358 o	17
	3	113 (13)	5.5 (16)	0.367 o	18
	Avg.	108 c	5.5 a	0.332 a	
Ear	0	87 (8)	14.0 (11)	0.246 m	16
	1	89 (9)	14.9 (9)	0.332 n	16
	2	95 (7)	14.1 (9)	0.363 o	17
	3	96 (8)	13.5 (8)	0.373 o	18
	Avg.	92 b	14.1 b	0.329 a	
Average over vegetative component	0	90 x¶	15.0	0.282 x	16
	1	90 x	15.0	0.345 y	16
	2	96 y	15.1	0.365 z	17
	3	97 y	14.5	0.371 z	18
ANOVA					
Source	df		$P > F$		
Plant position (PP)	3	0.004	0.45	<0.0001	
Vegetative component (VC)	2	<0.0001	<0.0001	<0.0001	
VC × PP	6	0.96	0.73	<0.0001	

† Numbers in parentheses are the coefficient of variation (%).

‡ Letters m, n, o indicate significant differences ($P < 0.05$) between means of each plant position within each vegetative component.

§ Letters a, b, c indicate significant differences ($P < 0.05$) between means across plant positions for each vegetative component.

¶ Letters x, y, z indicate significant differences ($P < 0.05$) between means across vegetative components for each plant position.

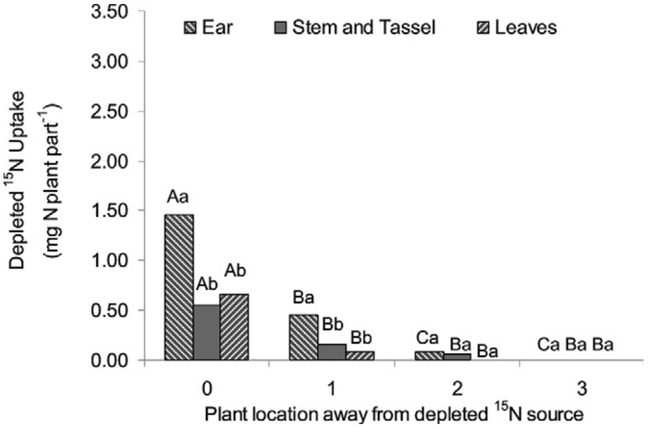

Fig. 3. Depleted ^{15}N uptake at R1 for each vegetative component within each plant position. Uppercase letters indicate difference ($P < 0.05$) for vegetative components across plant position. Lowercase letters indicate differences ($P < 0.05$) between vegetative components within each plant position.

^{15}N between the vegetative components of corn plants two and three positions away from the target plant.

Total depleted ^{15}N fertilizer uptake was greater in the immature ear than in the stem within corn plants positioned at zero and one (Fig. 3). When the depleted ^{15}N fertilizer uptake was averaged over vegetative components, the target plant contained significantly more than the first neighboring corn plants (data not shown). In addition, the first neighboring corn plants averaged more depleted ^{15}N fertilizer than those plants two and three positions away from the target plant. These data agree with the results reported for the V12 sampling because corn plants two positions or more away from the target plant did not take up significant amounts of depleted ^{15}N fertilizer (Table 2). It stands to reason that plants in adjacent rows would have limited access to the fertilizer N placed under plants that are a row-width away. The relatively short period between fertilizer N placement and plant sampling (7–10 d) in this study and the fact that all plants received the same amount of placed N fertilizer will reduce the plant competition effect compared to only fertilizing specific plants.

DISCUSSION

The relatively short exposure period of the roots to depleted-N fertilizer used in this study was chosen to assess the presence and activity of plant roots and minimize the possibility of lateral N movement in the soil. A plausible reason for the lower amount of depleted ^{15}N uptake at R1 than at V12 might be because the plants used in the second sampling were only exposed to the depleted ^{15}N fertilizer for 7 d compared with the 10 d of the first sampling (Fig. 2, 3). It should also be noted that the blanket early-season N application that preceded the VT application could have increased the size of the N pool and thus reduced the relative significance of the VT application. Finally, detailed biomass and N uptake studies have shown significantly reduced N uptake rates around the time of anthesis, regardless of the corn hybrid (Dennis Francis, 5 June 2007, personal communication).

The reduction in average N concentration in the stems between the two different sampling dates indicates the stem N was used to support the growth of the immature ear and

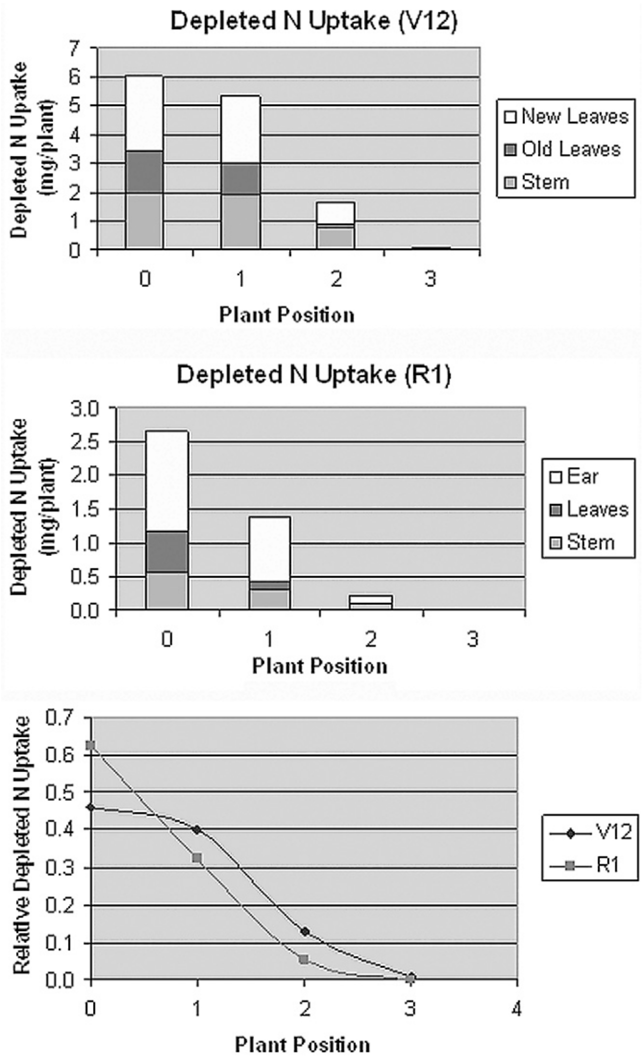

Fig. 4. Distribution of depleted ^{15}N uptake by corn at two growth stages and three mirrored plant positions relative to a single soil injection point of depleted ^{15}N fertilizer at position #0 (~18 cm between plants). Data compiled from Tables 1 and 2 to calculate mirrored effects.

kernels (Ta and Weiland, 1992; Below et al., 1981, 1985). The observation that the depleted ^{15}N applied at VT was mainly found in the ear illustrates the importance of having sufficient N for late-season uptake to maximize yields. These data indicate that N acquired by the corn plant at this growth stage may be rapidly transformed into substrates to support the development of new plant organs. The partitioning of late season N uptake into developing kernels was also reported by Ta and Weiland (1992) and Below et al. (1981).

Since the corn biomass weights and total N concentration were not considered significantly different between corn plant positions within each vegetative component, it is likely the root distribution and pattern in the soil was similar between individual corn plants. Our N application scheme and the way we sampled the plant parts into components rely on the assumption that N availability and root distribution were mirrored around our plants. This assumption would not be totally valid for situations with nonuniform plant spacing. Based on the distances between plants (~18 cm), these results indicate a single corn plant acquires a large portion of its in-season N from the soil volume between the immediate neighboring plants

(Fig. 4). This is in agreement with reports indicating the greatest density of a corn plant's roots is directly under the plant (Mengel and Barber, 1974) and decreases as horizontal distance increases from the plant (Crozier and King, 1993). Of the total depleted ^{15}N uptake at V12, roughly 46, 40, 13, and 1% were measured in the target, first, second, and third closest plants to the depleted ^{15}N source, respectively (Fig. 4). For the R1 sampling date, the values were 63, 32, 5, and 0%, respectively. These trends indicate that the plant's root domain retracted between V12 and R1. Further, data presented in Fig. 4 indicate that vigor of an individual plant measured with a crop canopy sensor realistically represents a soil foot-print that is ~36-cm long (two interplant distances in this study). Conversely, the results indicate that to assess the impact of a point N source in the soil, one would need to evaluate a vegetative footprint that is about 50 cm long (three plants in this study). These findings are in agreement with several studies conducted by other researchers who determined the optimum size needed for microplot techniques when using enriched ^{15}N fertilizers (Johnson and Kurtz, 1974; Jokela and Randall, 1987; Olson, 1980; Sanchez et al., 1987). Olson (1980) determined for broadcast N applications that corn plants in the row within a microplot that were 0.36 m from the border had significantly lower amounts of N derived from isotope-labeled fertilizer than corn plants that were spaced over one meter inside the microplot's edge. This is the same distance reported by Jokela and Randall (1987), who evaluated groupings of individual corn plants based on their distance from the border of the microplot. They determined corn plants needed to be collected a minimum of 0.38 m from the edge of a microplot. Their findings reflect the radius at which corn plants gained access to a different source of fertilizer N placed outside the microplot.

Our findings are also supported by Sanchez et al. (1987) who suggested the appropriate size of a microplot in Central Iowa for fall and spring applied N with either banded or broadcast applications. By using an iterative process, they estimated the percentage of fertilizer-derived N in the grain of an individual corn plant based on distance from the edge of the microplot. They stated grain N from an individual corn plant located 0.38 m inside the plot would have between 82% (spring banded applied) and 87% (fall surface applied) of the fertilizer N found in the grain from corn plants in the center of the plot. Conversely, N in the corn grain of an individual plant with a distance of 0.38 m outside the microplot border would have only 19% (spring banded applied) and 35% (fall surface applied) of the depleted ^{15}N compared with plants grown in the direct center of the plot. It should be noted that the cited distances of root exploration by other authors are confounded by the row spacing and plant densities, along with fertilizer placement in relation to the plant sampling strategies employed in each respective study. These confounding factors should also be considered in the present study where the data were collected at approximate distances of 18, 36, and 54 cm from the depleted ^{15}N source. One implication is that the 36 to 38-cm zone of influence indicated by past research and this study represents about one-half the distance between adjacent corn rows.

Relative to the feasibility for by-plant fertilization of corn, in-season N applications at V9 or so could be expected to have ~50% relative effectiveness (the other 50% shared by adjacent and nearby plants) and for by-plant applications at VT the relative effectiveness is likely to be somewhat higher (~60 to 65%). These relative effectiveness values would likely change if the period between N application and plant sampling increased because only ~10% of the depleted ^{15}N applied was taken up by the plants. It is presently impractical to position by-plant N applications beneath plants as done in this study. Variable–rate surface applications of liquid N near target plants is presently possible, but the effectiveness would likely be less than for injection of the fertilizer beneath each plant or even when injected near the plants or between the rows with a spoke injector (Blaylock and Cruse, 1992). Reasons postulated for the reduced effectiveness of surface N applications are volatile N losses and a more diffuse treatment area that is not intimately positioned among the roots. Making variable-rate N applications with a spoke-injector would be mechanically possible but if the goal is to strategically inject the fertilizer near the target plant the placement could only be approximate because the injection frequency is predetermined by the spoke-injection wheel.

CONCLUSIONS

Data presented in this paper indicate early season N uptake is mainly destined to support the development of the photosynthetic capacity (leaf expansion) of the corn plant. The finding that the stems decreased in N concentration from V12 to R1 is probably because the stem component at V12 contained undeveloped leaves that had expanded at R1.

Data obtained in this study indicate a single corn plant can encounter competition for applied N from the nearest neighboring corn plants and vice versa. The second nearest corn plants (~36 cm away) offered little competition for the depleted ^{15}N fertilizer when all plants received similar amounts of N fertilizer. These findings indicate the target plant acquired a majority (63%) of its in-season N supply from a horizontal radius of less than 0.18 m (~0.36 m in diameter).

Variable rate application schemes should realistically sense a three- to five-plant sequence when plants are ~18 cm apart because roots at the V12 and R1 growth stages were intermingled as far as 36-cm away from a point fertilizer N source. Data presented in this study indicate a single plant obtains most of its in-season N from a horizontal distance between the immediate neighboring corn plants when the N is placed directly under the plant. However, an individual corn plant can acquire between 33 and 40% of its fertilizer N from the soil area occupied primarily by its nearest neighbor when plants are spaced at ~18-cm intervals. Ultrafine spatial N management schemes that are aimed at increasing NUE could logically operate at a resolution that reflects the horizontal diameter at which plants obtain the majority of their N supply. The relative effectiveness of surface N application near a corn plant rather than point injection under selected plants could be the topic for future research.

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