Fertilizer Residence Time Affects Nitrogen Uptake Efficiency and Growth of Sweet Corn

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Understanding plant N uptake dynamics is critical for increasing fertilizer N uptake efficiency (FUE) and minimize the risk of N leaching. The objective of this research was to determine the effect of residence time of N fertilizer on N uptake and FUE of sweet corn. Plants were grown in 25 L columns during the fall and spring to mimic short-term N uptake dynamics. Nitrogen was applied either 1, 3, or 7 d before a weekly leaching event, using KNO_3 solution (total of 393 kg N ha^{-1}). Residence times (t_R) were t_R–1, t_R–3, and t_R–7 d before weekly removal of residual soil N. Plant N uptake was calculated by comparing weekly N recovery from planted with non-planted columns. During the fall, N uptake values at 70 d after emergence were 59, 73, and 126 kg N ha^{-1}. During the spring, corresponding values were 54, 108, and 159 kg N ha^{-1}. A linear response of plant growth and yield to the t_R was observed under cooler conditions, whereas a quadratic response occurred under warmer conditions. There was correlation between root length density and yield. It is concluded that increasing N fertilizer residence time, which is indicative of better irrigation practices, enhanced overall sweet corn growth, yield, N uptake, and FUE, consequently reduced the risk of N being leached below the root zone before complete N uptake.

Nitrogen has an important role in increasing crop production and in many cases it may be considered the most common growth limiting factor. Excessively high applications of N fertilizer are not uncommon in agricultural operations and N losses from cropping systems may thus be an important source of ground water pollution (Almasri and Kaluarachchi, 2007). Agricultural land planted with sweet corn in Florida was over 38,800 ha which represented about 16% of the total area planted in the U.S. (USDA, 2005). Approximately 50% of total N fertilizer applied was being taken up by the crop (Bundy and Andraski, 2005). Nitrogen fertilizer management practices typically include an application of 20 to 25% of the N at planting followed by one or two sidedress applications of the remaining N during the early part of the growth cycle (Hochmuth and Cordasco, 2000). Sweet corn is typically irrigated with overhead irrigation. Although overall water use efficiencies of irrigation systems are adequate, failure of growers to implement appropriate irrigation scheduling practices often results in over-irrigation. Thus, the low soil water holding capacity (8 to 10%) of the sandy soils common to Florida, which are very prone to nitrate leaching (Perrin et al., 1998), combined with excessive irrigation may result in appreciable N leaching losses. Optimization of fertilizer use efficiency (FUE) via improved irrigation and fertilizer management practices is therefore essential to minimize environmental impacts of commercial production operations. However, improving FUE will also require a better understanding of the interaction between N fertilizer application methods and timing with seasonal changes in crop N demand.

Crop N accumulation of sweet corn grown under field conditions ranged from 135 to 258 kg N ha^{-1} (Wiesler and Horst, 1992; Bundy and Andraski, 2005). Corn N demand is typically relatively high due to the great aboveground dry matter accumulation which forms a large N sink. Nitrogen uptake is initially driven by root uptake capacity and sink capacity of the shoots as affected by their growth rate. Overall plant N uptake is thus dependent on the availability of soluble carbohydrates in the roots (Henry and Raper, 1991) as well on environmental conditions such as temperature, water, and nitrate availability (Scholberg et al., 2002). Overall N uptake of sweet corn follows biomass accumulation and shows a lag phase (20–40 d) when leaf area and thus light interception hamper

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Abbreviations: DAE, days after emergence; FUE, Fertilizer-N uptake efficiency; NPA, nitrogen plant accumulation; RDM, root dry matter; RLD, root length density; t_R, residence time.

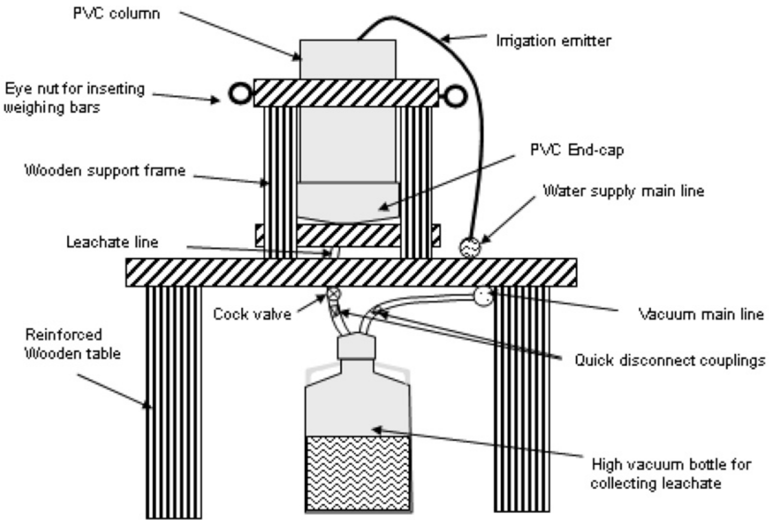

Fig. 1. Overview of soil N uptake monitoring (SUM) columns (Adapted from Scholberg et al., 2001).

growth rates, followed by a linear (rapid) growth phase, which culminates at about 40 to 45 d (Avila, 2006).The most critical phase for N supply is the grain filling stage when the canopy N levels typically decline as the plant progresses to maturity (Christensen et al., 1981) and retranslocation of N from leaves and the stem to ears predominate (Plenet and Lemaire, 1999).

Although corn has a high demand for nitrogen, many studies show that its utilization of fertilizer nitrogen is lower than 55% (Bundy and Andraski, 2005). Fertilizer recovery typically decreases with an increase in N application rates while timing of fertilizer application also affects fertilizer uptake efficiency in corn (Subedi and Ma, 2005). However, overall N recovery and efficiency of corn seems also to be impacted, to a large extent, by irrigation management practices (Kirda et al., 2005) and climatic conditions. Under water-limiting conditions, crop production increases proportionally to irrigation supply, and adequate water supply is thus critical to ensure maximum nitrogen use efficiency (Kramer and Boyer, 1995). However, for soils with poor water retention, application of excess water may promote displacement of nutrients before complete uptake has occurred (Zotarelli et al., 2008). Matching irrigation rates with crop demand and integrating information pertaining to the effective water-holding capacity of the effective root zone into actual irrigation scheduling techniques is thus required to minimize N leaching on poorly buffered sandy soils. Nitrogen uptake efficiency is typically closely related to N uptake characteristics of the root system and the residence time of nitrogen in the rhizosphere as dictated by rainfall, irrigation practices, soil type, and presence of mulch (Scholberg et al., 2002). Although there have been a wealth of studies outlining the effect of N rate and application methods on overall fertilizer response, relatively few studies elucidated the underlying mechanisms that control short-term uptake dynamics and thereby FUE in sweet corn production systems (Kristensen and Thorup-Kristensen, 2004; Bundy and Andraski, 2005).

The objectives of this study are to determine the effect of fertilizer residence time (t_R), on weekly N uptake, FUE, growth, and yield of sweet corn. Weekly applied fertigation solution was retained in the root zone for different time periods (residence times, t_R) to mimic the effect of N displacement due to a leaching irrigation event on FUE after a specific fertigation event. Our ultimate goal was to determine at what crop development stages N was used most efficiently and in this manner provide suggestions for improved fertigation practices that can reduce potential N leaching. Our hypothesis was that increasing the residence time (indicative of improved irrigation management practices) of fertilizer N in the root zone will improve FUE and thereby enhance plant growth and crop yield. Alternatively, fertilizer displacement below the root zone before complete crop N uptake will reduce FUE and thus will increase fertilizer cost and environmental impacts associated with commercial crop production systems.

Materials and Methods

Research was conducted at the Environmental Quality Research Lab at the Univ. of Florida, Gainesville, FL between September and December 2004 and April and July of 2006. To monitor N uptake, large soil N uptake monitoring (SUM) systems were built using a 50-cm length of PVC pipe with an internal diameter (i.d.) of 30.4 cm. The bottom of each column was fitted with a PVC end cap in which a center hole was drilled and threaded to fit a 1.27 cm outside diameter (o.d.) adaptor connecting to drainage with a valve to prevent premature N leaching. A 5 cm square, triple-folded piece of nylon screen was positioned above the center hole to retain sand in the columns (Fig. 1).

Columns were filled with 45 kg of sieved (<2 mm) Candler fine sand (Typic Quartzipsamments, hyperthermic, uncoated). This soil consists of 97% sand-sized particles, a saturated hydraulic conductivity of 35 cm h^{-1}, and contains 0.45 g C kg^{-1} (Carlisle et al., 1988). The outside of the columns was insulated with aluminum foil. Columns were placed in wooden crates to facilitate weighing required for ET calculations. The weighing procedure was done only in fall 2004. These crates were placed on reinforced wooden tables (1.0 × 2.7 × 0.9 m) on a small concrete slab surrounded by frequently mowed grass surface.

On 9 Sept. 2004 and 21 Apr. 2006, sweet corn (*Zea mays* var. *rugosa*, cultivar 'Saturn') seeds were sown in 12 SUM system columns, and thinned to two plants per column after germination. An additional 12 non-planted SUM system columns were included and used as control (reference) systems. Column spacing was 0.45 by 1.8 m and columns were randomized according to a complete block design with four replicates.

Treatments included three N residence time (t_R) treatments. Weekly applied fertigation was completely displaced below the root zone by leaching the soil solution with 2.0 pore volumes 1, 3, or 7 d after fertigation occurred. Nitrogen was applied at 0800 h either 1, 3, or 7 d before a weekly leaching event. Each column received 650 mL of solution each week containing 320 (Week 1–2), 650 (Week 3), 970 (Week 4), 1450 (Week 5–7), and 970 (Week 8–11) mg N wk^{-1} from purified grade KNO_3 (Fisher Scientific, Pittsburgh, PA, USA), which is translated to 393 kg N ha^{-1} applied at the end of the season. The N solution was mixed with a complete N-depleted nutrient solution composted by K_2HPO_4, $MgSO_4$; $CaCl_2$, H_3BO_3; $MnCl_2$; $ZnSO_4$; $CuSO_4$; H_2MoO_4; and iron Sequestrene 138 (Maust and Williamson, 1994). On treatment application days, the columns not receiving the fertilizer solution received 650 mL water instead. We assumed a plant population of 75,000 plants ha^{-1} for conversion from the hectare basis unit.

Columns were irrigated with four "tube weight" drip emitters (Chapin EW50-36, Watertown, NY) per column resulting in an irrigation rate of 44.4 L h^{-1}. Columns were weighed before and after leaching events. Air temperatures were recorded at 30-min intervals using "Watchdog" 450 temperature sensors (Spectrum Technology, Plainfield, IL). Rainfall gages were placed adjacent to columns. Rainfall was recorded daily and changes in column weights, corrected for added fertigation, irrigation, and rainfall amounts, were used to calculate weekly crop water use of individual columns.

At the end of an uptake period (7 d), residual soil N was extracted with excess water (>18 L, approx. 2 pore volumes) and leachate was collected in 20 L vacuum containers (Nalge Nunc International, Rochester, NY). Preliminary studies had shown that this extraction volume resulted in N recovery >99% (Scholberg et al., 2001). The following methodology was used to ensure high extraction efficiency of residual soil N: A ponding period (irrigation only) between 3 and 5 min was used to cover the soil with 1 cm of water to bring any N that might have accumulated at the soil surface back into solution. Subsequently, the valves at the bottom of the uptake columns were opened to allow drainage and N leaching to commence. Drainage tubes were hooked up to the leachate collection containers, that were also connected to a vacuum line to maintain a partial (20 KPa) vacuum at the bottom of the column. Moreover, this partial vacuum, combined with high irrigation rates and the high hydraulic conductivity of the soil also resulted in a rapid and intensive residual soil nitrate extraction cycle that continued for a total of 27 min. This leaching cycle was then followed by a drying cycle (vacuum only) which was maintained for another 30 min. During this cycle, residual volumetric soil water content was reduced to 10 to 15%. This was to prevent excessive wet conditions at the bottom of the column (the so called 'container capacity' phenomena) which may result in an anaerobic condition, and may also induce root rot and/or denitrification which does not occur for well-drained soils under field conditions. A detailed description of the SUM system design and its use is presented elsewhere (Scholberg et al., 2001).

After completion of the drying cycle, containers were disconnected from the drainage and vacuum ports before determining leachate volume gravimetrically with a waterproof bench scale (I20W, Ohaus, Florham Park, NJ). Representative subsamples were filtered (Whatman #5, Maidstone, UK) and stored in 20 mL scintillation vials at –20°C until analysis. Samples were analyzed using an air-segmented automated spectrophotometer (Flow Solution IV, OI Analytical, College Station, TX) coupled with a Cd reduction approach (modified USEPA Method 353.2; Jones and Case, 1991). Fertilizer N uptake for a specific t_R treatment ($U_{treatment}$) was calculated as: $U_{treatment} = V_{reference} * [N_{reference}] - (V_{treatment} * [N_{treatment}])$ where V is the volume of the leachate and $[N_{treatment}]$ and $[N_{reference}]$ are the measured N concentrations of leachate from the treatment and reference columns, respectively.

Soil and air temperatures were recorded at 15-min intervals with compact dataloggers (Spectrumtechnology, Springfield, IL). Daily values of degree days were calculated as $(T_{average} - T_{base})(1\ d)$, where $T_{average}$ equals average daily temperature (°C). Base temperature (T_{base}) assumed 10°C.

Plants were harvested at maturity stage, when the pollination silks were dried and the kernels were still "milky," on 30 Nov. 2004 and 23 July 2006 by cutting the stems at the soil level. Root systems were carefully excavated from the column and rinsed. Root, shoot, and ear tissues were dried for 3 d at 65°C for subsequent dry weight determinations. For spring 2006 root samples, a subsample of 5 g of roots was scanned and root length was measured by WINRHIZO software (Régent Instrument Inc., Canada). Afterward, tissue samples were ground in a Wiley mill to pass through a 2-mm screen, and a thoroughly mixed 5-g portion of each sample was stored. Tissue material was digested using a modification of the aluminum block digestions procedure of (Gallaher et al., 1975) and analyzed for total Kjeldahl N at the Analytical Research Lab [Univ. of Florida, Gainesville; USEPA Method 351.2 (Jones and Case, 1991)].

Weekly FUE was defined as N uptake divided by the amount of N supplied from weekly fertigation. Measured weekly N uptake values were integrated over the entire growth season and used to calculate overall FUE. Potential N leaching values were calculated by taking the difference between weekly applied N and plant N uptake rates.

Statistical analyses were performed using SAS PROC GLM for analysis of plant biomass and N accumulation and SAS PROCMIX Model for weekly and cumulative plant N uptake, fertilizer use efficiency, and potential N leaching (SAS, 2002). Means were compared using the Duncan's test with a *P* value of 0.05. Orthogonal polynomial contrasts were also used to test for linear and/or quadratic responses to residence time for selected crop parameters.

Results and Discussion

Climate and Crop Water Use

Measured climatic parameters showed some similarities between spring and fall seasons during initial vegetative growth (Fig. 2). Average air temperature and cumulative uptake temperature were 22.4°C and 608°Cd, respectively, until 52 d after emergence (DAE). During the fall, after 44 DAE, temperatures dropped to 15.1°C at 48 and 58 DAE, and to below 13°C 3 d before the final harvest. During the spring, the lowest average temperature was 21.8°C at 46 DAE while the average temperature ranged between 24.1 to 29.2°C during the reproductive stage. As a result of different average temperatures during the corn maturity the cumulative uptake temperatures were 758 and 927°Cd for the fall and spring season, respectively.

Weekly crop water use increased over time until 50 DAE during the fall (Fig. 3A). This trend was related to the relatively high overall daily temperatures during initial vegetative growth but lower temperatures during crop maturation, which resulted

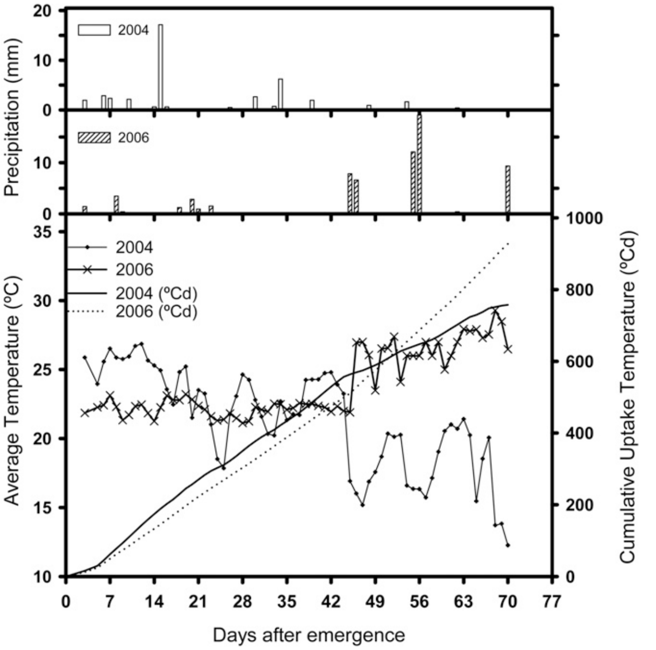

Fig. 2. Average air temperatures (dotted lines, left axis), cumulative uptake temperature (non-dotted lines, right axis), and precipitation at the experimental location during fall 2004 and spring 2006.

in a gradual decline in weekly evapotranspiration (ET) rates. After 54 DAE, crop water use drastically decreased to about 50% for all treatments (Fig. 3A) which was related to the reduction in air temperatures occurring between 48 and 70 DAE. Crop water use increased with t_R, and cumulative values were 101, 177, and 261 mm for t_R–1, t_R–3, and t_R–7, respectively. Columns were always close to field capacity so in the absence of soil moisture limitation, crop water use was proportional to plant size and canopy volume. As a result, differences in crop water use were mainly attributed to the beneficial effect of higher t_R on plant growth and root length density (Table 1). During the spring higher crop water use was expected since higher average temperatures were registered during the reproductive stage.

Weekly Crop Nitrogen Uptake and Overall Nitrogen Accumulation

The patterns of weekly N uptake rates (Fig. 4AB) were similar for both seasons and followed crop water use curves (Fig. 3A). During the exponential plant growth phase, the N uptake curves showed a pronounced increase in N uptake rates during the first 6 to 7 wk after emergence followed by a period of decreasing N uptake rate. This may be related to a redistribution of assimilate from vegetative to reproductive structures (Plenet and Lemaire, 1999).

During the first week, N uptake rate was very low, between 7 and 29 mg N pl^{-1} wk^{-1} (Fig. 4AB), which translates to 0.5 to 2 kg N ha^{-1}. During the following next 2 wk, the N uptake rate slightly increased and the accumulated N uptake at 21 DAE reached 15 to 23 kg N ha^{-1} for t_R–7; 6 to 14 kg N ha^{-1} for t_R–3, and 3 to 7 kg N ha^{-1} for t_R–1 (Fig. 4CD). Relatively low initial N uptake during the first 2 to 3 wk after emergence may be related to several factors. The small leaf area limits carbon supply to the roots (root uptake capacity) and formation of new shoots (sink capacity). Moreover, initially roots were confined to a very small soil zone and the majority of soil volume was not effectively exploited by plant roots (Clarkson, 1985). Overall plant N uptake has been observed to be proportional to root length (Wiesler and Horst, 1992). Three weeks after emergence, overly short retention times (t_R–1 and t_R –3) also resulted in an appreciable reduction of plant N uptake rate compared to t_R–7. This reduction in N uptake during initial growth directly reduces the potential rate of protein synthesis which in turn affects CO$_2$ assimilation (Lawlor et al., 1989). Over time this also reduces the overall sink uptake capacity during subsequent plant growth phases.

During the fall, N uptake peaked at 48 DAE and uptake rates were 318, 344, and 441 mg N pl^{-1} wk^{-1} for t_R–1, t_R–3, and t_R–7, respectively (Fig. 4A). One week later, corresponding cumulative N uptake rates (expressed on an area basis) started to decrease. During the spring, maximum N uptake occurred 1 wk earlier, at 42 DAE, with 206, 314, and 440 mg N pl^{-1} wk^{-1} for t_R–1, t_R–3, and t_R–7, respectively (Fig. 4B). After 42 DAE, N uptake rate also decreased for all treatments during the spring. Although there was a decrease

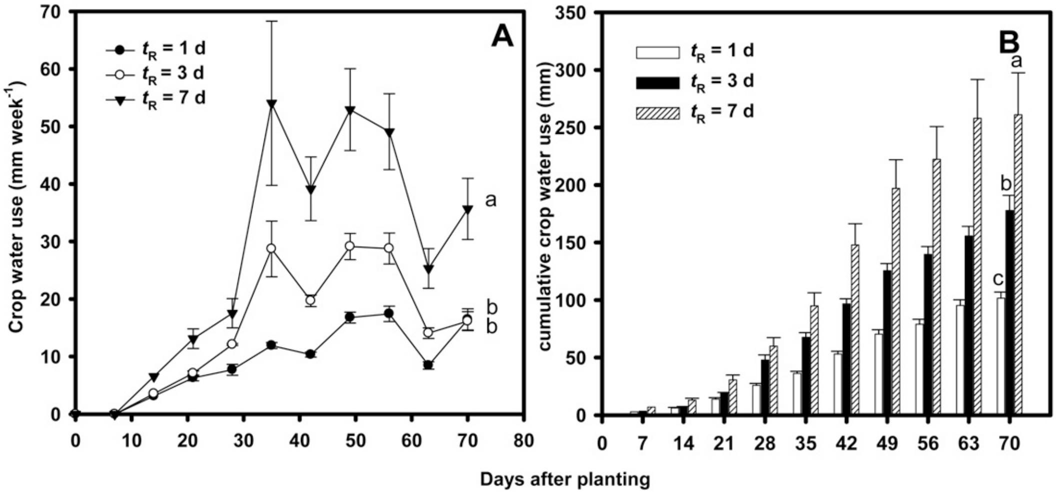

Fig. 3. Weekly (A) and cumulative (B) crop water use of corn as effected by residence time (t_R = 1, 3, or 7 d) for fall 2004. Error bars represent standard error from the mean, n = 4. Treatment means followed by the same letter are not different according to Duncan's test at $P \le 0.05$.

Table 1. Dry matter and N accumulation, tissue nitrogen concentration, root length density (RLD) and fertilizer use efficiency (FUE) of sweet corn affected by N residence time during fall 2004 and spring 2006.

t_R	Dry matter					N concentration			N accumulation				
	Shoot	Ear	Roots	Total	RLD	Shoot	Ear	Roots	Shoot	Ear	Roots	Total	FUE
d	g plant^{-1}				cm cm^{-3}	mg g^{-1}			mg plant^{-1}				%
Fall 2004													
t_R-1	12.3 b†	11.3 b	2.6 a	26.1 b	n.d.§	13.4 b	14.6 b	9.8 a	161b	165 b	25 a	355 b	16.8 b
t_R-3	19.3 b	13.9 b	3.6 a	36.8 b	n.d.	17.0 a	15.4 ab	11.6 a	330 ab	215 ab	41 a	586 ab	20.6 b
t_R-7	30.2 a	43.8 a	7.0 a	80.9 a	n.d.	17.2 a	16.0 a	10.1 a	520 a	705 a	70 a	1315 a	35.6 a
Contrast‡	L*	L*	L*	L*	–	L*	L*	L^{ns}	L*	L*	L^{ns}	L*	L*
	Q^{ns}	Q^{ns}	Q^{ns}	Q^{ns}	–	Q^{ns}	Q^{ns}	Q^{ns}	Q^{ns}	Q^{ns}	Q^{ns}	Q^{ns}	Q^{ns}
Spring 2006													
t_R-1	14.4 b	11.6 c	2.2 c	28.1 c	2.2 c	11.1 b	16.6 b	9.6 a	160 b	195 c	21 b	376 c	14.7 c
t_R-3	42.3 a	44.3 b	6.5 b	91.7 b	5.5 b	15.8 a	17.4ab	10.8 a	670 a	770 b	70 a	1510 b	29.4 b
t_R-7	46.0 a	54.2 a	8.1 a	107.8 a	6.5 a	15.3 a	18.4 a	10.5 a	705 a	995 a	85 a	1785 a	43.2 a
Contrast‡	L**	L**	L**	L**	L***	L*	L*	L^{ns}	L*	L*	L*	L**	L**
	Q**	Q*	Q*	Q*	Q*	Q*	Q*	Q^{ns}	Q*	Q^{ns}	Q^{ns}	Q**	Q^{ns}

† Treatment means are not different if followed by the same letter ($P \leq 0.05$).

‡ Orthogonal polynomial contrast for the effect of residence time (ns = not significant, L = linear, Q = quadratic, * $P \leq 0.05$, **$P \leq 0.01$ and ***$P \leq 0.001$).

§ n.d., not determined.

in N uptake rate during the spring, it did not occur as drastically as occurred with corn plants in the fall which may be related to the increase in temperature toward the end of the spring growing season. Water and nitrate uptake is temperature dependent and nitrate uptake rate tends to be reduced at lower temperatures (Clarkson and Warner, 1979; Abbasalani and Hay, 1983). Moreover, for corn development, the beginning of grain filling is considered a critical phase of N supply because N uptake declines as the plant progresses to maturity (Christensen et al., 1981), mainly due to the reduced transport of carbohydrates to the roots and remobilization of N from vegetative compartments to the reproductive parts. Plenet and Lemaire (1999) observed that from the silking stage to maturity about 65% of the 173 kg N ha^{-1} accumulated in the ears was remobilized from vegetative compartments and about 60 kg N ha^{-1}was taken up from the soil.

Residence time of applied N in the upper soil layer had a significant effect on plant N uptake and N accumulation. Weekly N uptake values were integrated to calculate the cumulative N uptake per ha. The overall N uptake and cumulative N uptake were significantly higher for t_R–7 for both seasons, on the order of 122 and 160 kg N ha^{-1} for fall and spring, respectively (Fig. 4C and D). During the fall, there was no difference on total cumulative N uptake between t_R–3 and t_R–1 and corresponding values were 70 and 74 kg N ha^{-1}, respectively. Conversely, during spring, the t_R–3 accumulated 50% more N than t_R–1, which accrued only 54 kg N ha^{-1} (Fig. 4D). The increase in N accumulation with t_R may be related to an increase in plant growth, reduced leaf senescence, and increased availability of soluble carbohydrates to roots (Tolleyhenry et al., 1988), resulting in an increasing sink capacity (Bassirirad, 2000) and thereby more complete N uptake.

Crop Growth and Yield

During the spring and fall, corn total dry weight and N accumulation increased linearly with increasing t_R, the only exception being root N accumulation during the fall (Table 1). During the spring, the increase in dry matter and N accumulation was quadratic, indicative of a saturation response (Clarkson, 1985), although these trends were not significant for N accumulation by roots and ears. As discussed previously, relatively low temperatures during the second growth stage greatly reduced overall corn N uptake and thereby also growth compared to spring. During the fall t_R–7 and t_R–3 accumulated 25 and 60% less dry matter than the corresponding treatments during spring, respectively. In addition, during the fall overall growth was also similar for t_R–1 and t_R–3. Corn biomass accumulation for the t_R–1 treatment during the fall and spring was relatively similar, which indicated that, for this particular treatment, instead of temperature, N supply was the most limiting factor to plant growth.

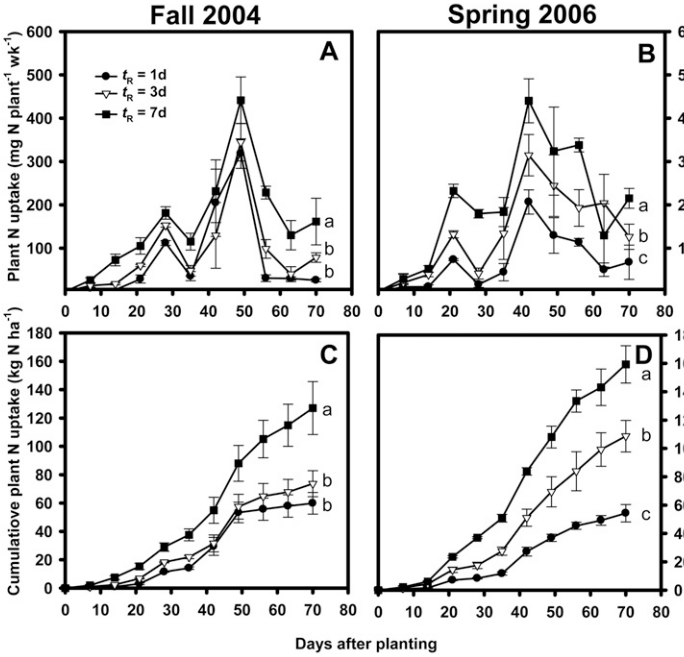

Fig. 4. Effect of residence time (t_R = 1, 3, or 7 d) on the weekly N fertilizer uptake per plant, (A) fall 2004 and (B) spring 2006. Calculated cumulative N uptake per ha during (C) fall 2004 and (D) spring 2006 of sweet corn. Error bars represent standard error from the mean, n = 4. Treatment means followed by the same letter are not different according to Duncan's test at $P \leq 0.05$.

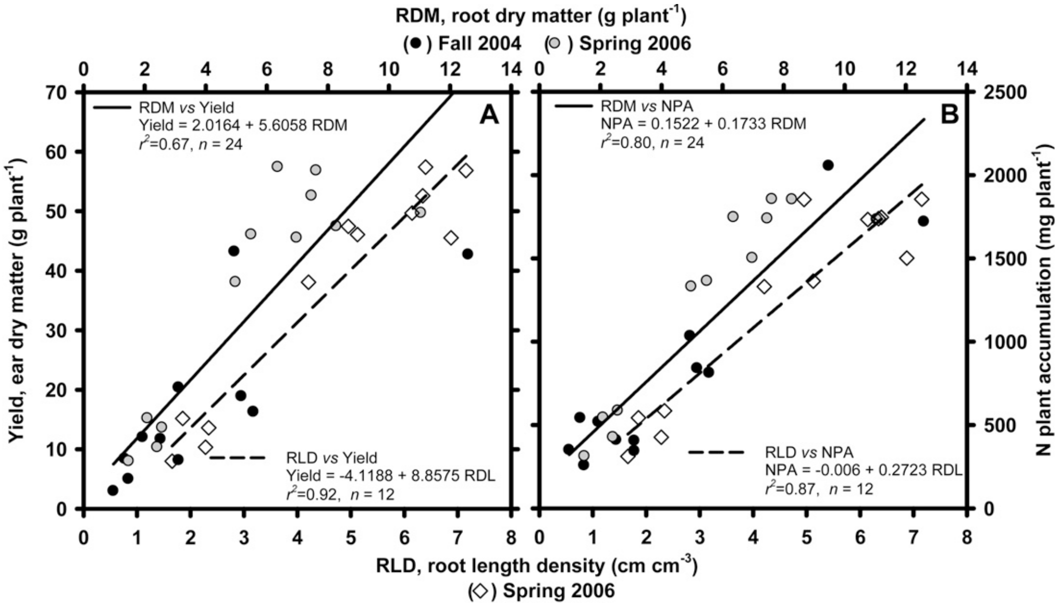

Fig. 5. Correlation between root length density (RLD, bottom axis) or root dry matter (RDM, top axis) versus (A) ear dry matter (yield, left axis) and (B) N plant accumulation (right axis) for corn cultivated during fall 2004 and spring 2006.

Root length and root density distributions are among the key factors controlling water and N uptake by corn plant. An increase in N residence time resulted in greater root weight and root length, and root weight increased linearly with residence time. During the spring, t_R–3 and t_R–7 accumulated 3 and 3.8 times more root biomass than t_R–1, respectively, whereas the t_R–3 treatment had significantly lower root mass compared to the t_R–7 treatment. Moreover, root length density (RLD) significantly decreased in the order t_R–7 > t_R–3 > t_R–1, which is in agreement with reports of RLD increasing with N supply (Maizlish et al., 1980; Wiesler and Horst, 1992). Both root dry matter (RDM) and RLD showed a significant positive correlation ($r^2_{\text{RDM}} = 0.80$ and $r^2_{\text{RLD}} = 0.87$) with total N plant accumulation (Fig. 5B). However, in terms of corn yield, RLD accounted for a larger fraction in overall yield variability ($r^2_{\text{RLD}} = 0.92$) compared to total root biomass ($r^2_{\text{RDM}} = 0.67$). From a mechanistic perspective this observation makes sense since RLD is a better indicator of root uptake capacity because it is closely linked to ability of roots in taking up nitrate (Lawlor, 2002). Although N application tends to enhance shoot growth more compared to root growth (Leskovar et al., 1989; Kramer and Boyer, 1995), the shoot to root ratio of corn was similar across treatments; the values ranged between 9.2 and 10.6 for fall and 12.6 and 13.2 for spring (data not shown).

Total ear yield increased with retention time (Table 1). During the spring, increasing t_R from 1 to 3 d increased yields by a factor 3.3. Corresponding fresh ear yields on a hectare basis were 4.3, 16.6, and 20.3 Mg ha^{-1} during spring and 4.3, 5.2, and 16.4 Mg ha^{-1} during the fall. The values of t_R–7 were similar to those reported under field conditions with equivalent N fertilization rate (Hochmuth and Cordasco, 2000; Bundy and Andraski, 2005; Dukes and Scholberg, 2005; Avila, 2006).

Although the growth and yield responses to extending t_R were most pronounced between 1 and 3 d during the spring and 3 and 7 d during the fall, overall plant growth and ear yields were greatest for the t_R–7 treatment. It should be noted that the yield response to t_R is similar to that typically observed in N rate studies (Mackay and Barber, 1986; Bundy and Andraski, 2005; Avila, 2006), although overall weekly N rate in the current study was the same across all t_R treatments. A similar response was also observed for citrus (Scholberg et al., 2002) and for pepper. It appears that extending t_R may have a similar effect as increasing N fertilizer rate. So it could be argued that improved irrigation practices will increase t_R and thereby could allow growers to attain similar or better yields at reduced fertilizer application rates.

Tissue Nitrogen Concentration and Accumulation

Root tissue N concentration was not affected by t_R in either season (Table 1). During the spring, shoot tissue N concentration increased quadratically and were similar for both t_R–3 and t_R–7 treatments (Table 1). Although shoot growth also showed a quadratic response, in this case the linear effect was also significant and tissue concentration showed a more continuous increase up to the highest t_R value. There was also a significant effect of t_R on ear N concentration between t_R–1 and t_R–7. In terms of increases in tissue N concentration, going from a 1- to 3-d t_R resulted in a 21 to 30% increase in N concentration of shoots compared to a 5% increase in N concentration of ears. Extending N retention from 3 to 7 d resulted in a +2 and −3% change in shoot N concentrations for fall and spring, respectively. Compared to changes in shoot growth, the relatively small increases and/or slight decreases in tissue N concentration may be related to N dilution in the dry matter associated with greatly increased growth rates (Ingestad, 1982).

Total N accumulation increased linearly with t_R whereas shoot and total N accumulation showed a quadratic response to the t_R during the spring growing season only (Table 1). In terms of crop N accumulation, maintaining N in the root zone for 3 vs. 1 d resulted in a 104, 30, 64, and 65% rate of increase in shoot, ear, root, and total plant N accumulation, respectively, during the fall. During the spring, N accumulation was higher than in the fall and the corresponding values were 318, 294, 233, and 300%, respectively. Extending N retention from 3 to 7 d resulted in 124 and 13% increases in total N accumulation for fall and spring, respectively.

Fertilizer Uptake Efficiency

Overall FUE values decreased in the order t_R–7 > t_R–3 ≥ t_R–1 for both the fall and the spring seasons (Table 1, Fig. 6AB). Results for the t_R–7 treatment were comparable to reported values for FUE of corn under field conditions fertilized at similar N rates (Bundy and Andraski, 2005).

Fertigation and plant growth rate play a critical role in determining FUE and crop N utilization. On sandy soils with poor nutrient retention capacities, applying N in phase with crop demand is a prerequisite to ensure optimal FUE. It appears that current N recommendations reflect this process adequately since actual cumulative N application rates match cumulative N accumulation rates (Fig. 4) relatively closely. However, enhancement of N retention significantly affected the root length distribution (Table 1) and thus the N uptake capacity during the plant growth period. As a result, overall FUE values were very low for t_R–3 and t_R–1 and in these particular cases, N recommendations would need to be in excess of actual crop demands to assure that N is not limiting crop growth. Alternatively, more frequent (continuous) fertigation and/or irrigation at initial plant growth phase may be beneficial to sustain adequately high N concentrations and soil moisture content in a relatively small spherical soil volume surrounding the plants (Muñoz-Carpena et al., 2005).

Potential Nitrogen Leaching

During initial growth, calculated potential N leaching rates closely followed N application rate and increased from 12 kg N ha^{-1} wk^{-1} during the first 2 wk to 58 kg N ha^{-1} wk^{-1} at Week 5 (Fig. 7A and B). Increasing residence time had a limited effect during initial growth, since overall plant uptake capacity was probably limiting. However, after this period, a pronounced difference occurred and at 49 DAE, potential cumulative N leaching was 158, 138, and 69 kg N ha^{-1} for the t_R = 1-, 3-, and 7-d treatments, respectively, during the fall and 191, 129, and 60 kg N ha^{-1} for the same sequence of spring treatments (Fig. 7 C and D). Between 35 and 56 DAE, the period characterized by the greatest N demand and an increase in crop water use (Fig. 3), also showed a sharp decrease in potential N leaching rates (Fig. 7AB). Similar findings were reported for citrus where an increase in FUE (and thus a decrease in potential N leaching) was closely correlated to an increase in canopy size and crop water use (Scholberg et al., 2002). Cumulative potential N leaching rates were 253, 223, and 101 kg N ha^{-1} for the t_R = 1-, 3- and 7-d treatments, respectively, for fall and 282, 159, and 85 kg N ha^{-1} for the same order of treatments for spring (Fig. 7CD).

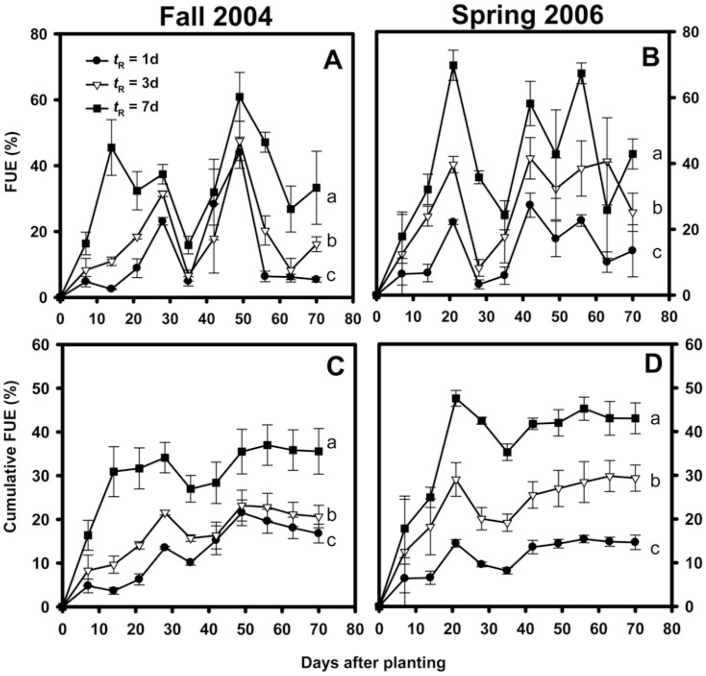

Fig. 6. Effect of residence time (t_R = 1, 3, or 7 d) on the calculated weekly N fertilizer uptake efficiency (A) and cumulative N fertilizer uptake efficiency (FUE) of (B) sweet corn. Error bars represent standard error from the mean, $n = 4$. Treatment means followed by the same letter are not different according to Duncan's test at $P \leq 0.05$.

Conclusions

Initial corn N uptake rates were very low during the first 2 wk. Therefore, excessively high initial N application rates will

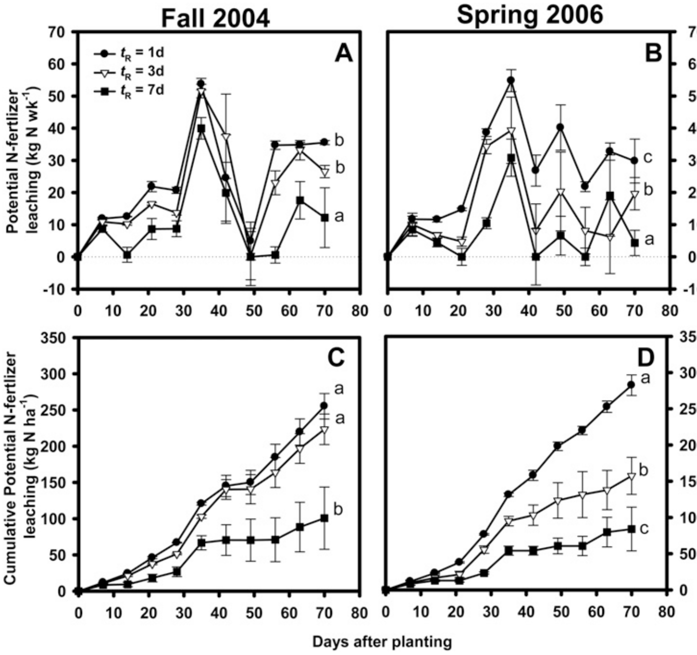

Fig. 7. Effect of residence time (t_R = 1, 3, or 7 d) on the calculated weekly potential N fertilizer leaching rate in kg N ha^{-1}, (A) fall 2004 and (B) spring 2006. Cumulative potential N leaching during (C) fall 2004 and (D) spring 2006 of sweet corn. Treatment means followed by the same letter are not different according to Duncan's test at $P \leq 0.05$.

invariably reduce fertilizer uptake efficiency. However, adequate N supply is still needed to ensure optimal growth and to enhance canopy build up, which in turn will provide assimilates for root system expansion which is critical for nutrient interception capacity. Crop N uptake capacity was greatest toward the end of the linear growth phase (49 DAE) due to adequate sink capacity concurring with high N application rates and optimum extraction efficiency of the root system. The premise that sound irrigation management can greatly enhance N retention in the active root zone resulting in improved FUE appears to be valid. Based on the results from this study, it is concluded that increasing N fertilizer residence time for a minimum of 7 d, indicative of better irrigation practices, enhanced overall plant growth, N tissue concentration, crop yield, and FUE.

Excessively high N application rates will invariably increase required uptake periods and hence also increase the risk of N being leached below the active root zone before complete N uptake. Increased nutrient retention will greatly enhance FUE, consequently decreasing N fertilizer rates required for maximum production and also potential N leaching.

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