

NITROGEN MANAGEMENT
WITH POLYMER-COATED UREA
FOR PROCESSING CARROT PRODUCTION IN MICHIGAN

By

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ABSTRACT

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Nitrogen (N) management in processing carrot (*Daucus carota* L.) is challenging because it is a long season crop grown on sandy soils. In addition, carrot growers must achieve a balance to obtain optimal yields and healthy tops for mechanical harvest, while avoiding nitrate accumulation in roots, and N losses to the environment. Three field studies were conducted to help characterize the effects of N rate, material and timing on carrot quality and yield. The first was a 2-year field study to determine the impact of N fertilizer material (urea treated with a urease inhibitor [U+UI] vs polymer-coated urea [PCU]), rate, and application timing on 1) carrot quality and yield; 2) petiole strength; and 3) carrot root nitrate (CRN) accumulation. Treatments consisted of 4 N rates (67, 101, 135, and 168 kg N/ha); three application systems (Grower Practice, Early PCU and Delayed PCU) and two N fertilizer materials (U+UI and PCU). The results of the 2-year study showed that both rate and system had little detectable effect on petiole strength. In contrast, CRN was affected by system and rate in 2013; the Early PCU system had greater CRN; N rate effect on CRN showed significantly higher accumulation of CRN at the highest N rate. In 2014 the effect of N rate on CRN varied with system; specifically, CRN was highest under Grower Practice at the highest N rate. The second field study evaluated three late-season (Aug-Sept) N management systems in a grower field: 1) a single application of PCU (Late PCU); 2) a single application of U+UI (Late U+UI); and 3) four split applications of foliar applied UAN (Late Foliar). In the second study, the only system effect was on CRN where the Late Foliar system had the lowest CRN (at $P=0.0670$). The third study evaluated the impact of four late-season rates of U+UI: 0, 25.2, 50.4, and 75.7 kg/ha. In the third study, CRN and shoot biomass were generally higher at the higher late-season N rates, but this did not translate into detectably greater petiole strength. Contrary to expectations, high late season N rates resulted in a marginally significant ($P=0.07$) increase in yield.

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This thesis is dedicated to:
my wife and daughter who have supported me in so many ways on this journey
and to my parents, without whom I would not be here.

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- Figure 2.1: N rate and system effects on carrot root nitrate (CRN), 2014. The grower practice had significantly higher CRN compared to the other systems at the 168 kg N/ha rate ($P=0.005$). 34

KEY TO ABBREVIATIONS

CRN	Carrot root nitrate
cv.	Cultivar
ESN	Environmentally Smart Nitrogen (Nutrien [formerly Agrium] Saskatoon, SK, Canada)
N	Nitrogen
NH_4^+	Ammonium
NO_3^-	Nitrate
PCU	Polymer-coated urea
UAN	Urea ammonium nitrate
UI	Urease inhibitor

CHAPTER ONE: Introductory Literature Review

Nitrogen management in carrot. In Michigan processing carrot (*Daucus carota* L.) production systems, growers typically top-dress urea (46N-0P-0K) treated with the urease inhibitor Agrotain[®] (U+UI) (Koch Agronomic Services, Wichita, KS, USA) up to 5 times to supply nitrogen during the growing season. Urease inhibitors help reduce N lost to volatilization as ammonia by inhibition of the enzyme urease, and their activity typically lasts 2-3 weeks (Steinke and Bauer, 2017). An alternative to soluble urea is a polymer-coated urea (PCU) fertilizer material, called “Environmentally Smart Nitrogen” (ESN[®]) (42N-0P-0K) (Nutrien [formerly Agrium] Saskatoon, SK, Canada). PCU works by protecting the urea prill by encapsulation in a polymer shell. The polymer shell is permeable, allowing water to infiltrate and dissolve the urea, after which it is slowly released through the shell over approximately 40 days (Golden et al, 2011). Nitrification inhibitors are another type of N stabilizer. They work by keeping N in the ammonium form by slowing the activity of enzymes and bacteria that convert ammonium to nitrate (Steinke and Bauer, 2017). Keeping N in the ammonium form helps reduce leaching which helps keep N in the rooting zone where it is available to plants.

N prices have been volatile over the last decade and are expected to continue to rise with the price of fossil fuels. In addition, each N top-dress application is estimated to cost approximately \$25/ha not including N material costs (Edwards et al., 2014). Therefore, optimizing nitrogen management is a cost-saving endeavor. Furthermore, current N management techniques involve multiple passes of heavy equipment which cause soil compaction which can negatively affect carrot root development thereby decreasing carrot quality (Taksdal, 1984). More efficient N sources and application methods could reduce input costs by more efficiently supplying N and allowing growers to reduce overall N use and equipment traffic on the field.

Controlled release N Fertilizer. PCU has been available for over 20 years, but the economic impact of its use in carrots is not clear. Although PCU’s cost 13 to 22% more than U+UI, potential savings in N requirements and application costs, coupled with possible improvements in crop quality or

harvestable yield, may justify its use. In the past, the higher price of PCU compared to conventional soluble N sources was thought to outweigh the benefits it provides in many crops (Guertal, 2009). However, Wilson et al. (2009), showed that, since prices of PCU have come down, PCU had similar net returns to split applications of soluble N in potato. It is important to note that PCU becomes more cost effective when N fertilizer prices are high. Benefits of PCU have also been shown in vegetable crops such as bell pepper where comparable yields to conventional split applications of N can be achieved using controlled release N materials applied before planting (Guertal, 2000).

A potential negative of using PCU as a top-dress N material is that it can float away from the intended placement in heavy rainfall. If this occurs, N supply is patchy and can have detrimental effects on carrot yield and quality. Therefore, shallow incorporation, or deep placement with planting or tillage equipment is often recommended for PCU.

The release pattern of N from PCU increases with temperature when moisture is not limiting (Gandeza et al., 1991). Similarly, carrot growth responds proportionally as temperature increases to a point, after which it declines (Finch-Savage et al., 2001). This indicates that PCU may be able to supply N to the carrot crop at a rate that better approximates the timing of carrot N consumption. However, if conditions are suboptimal for N release from PCU, the crop may be starved of needed N, potentially resulting in reduced carrot yield and quality.

Carrot root nitrate. Nitrogen management can also influence profitability through its impacts on carrot quality. An emerging area of concern for some processors is nitrate content in the carrot root (Gerber, personal communication). If nitrate levels are high enough in food they can have detrimental health effects on consumers, especially infants (Santamaria, 2006). Warncke (1996) showed that nitrogen fertilizer applications late in the season resulted in higher carrot root nitrate (CRN) concentrations and did not increase root yield. Both Boskovic-Rakocevic et al. (2012) as well as Gajewski et al. (2009) reported higher CRN at higher rates of N fertilization. On the other hand, Gutezeit (1999) reported that nitrate content in carrot taproots does not appear to be correlated with N fertilization. Conventional U+UI nitrogen top-dress application can lead to peaks and valleys in plant available nitrogen, whereas, PCU

provides a more even dose over time. The elimination of the peaks in N may help maintain low or reduced nitrate content in carrot products. Also, PCU may allow for a reduction in the optimal N rate and lead to fewer cracked carrot defects (Hartz et al., 2005). N management has also been shown to influence other quality parameters, including sugar levels, and compounds influencing flavor (Hochmuth et al., 1999).

Petiole strength. N management practices may also influence harvest efficiency and thereby act on profitability. In order to achieve maximum harvested yield, the carrot tops must be strong enough to withstand the abuse of top-pull harvest equipment. Carrot leaf blight caused by *Alternaria* and *Cercospora* is a major concern in top-pull harvested carrots due to both the direct negative effects of foliar disease on photosynthesis and carrot yield, and the indirect effect due to losses from carrot top breakage during harvest (Bounds et al., 2006; Rogers and Stevenson, 2006). Although they did not formally measure petiole strength, Bounds et al. (2006) found that as petiole health (rated visually) declined, mechanical harvester efficiency also declined. Carrot top biomass has been reported to be more responsive to N fertilization than root biomass, accumulating greater dry biomass per unit N applied (Westerveld et al. 2006, Warncke 1996, and Makries and Warncke 2013). Even though strong tops are important for harvest efficiency, it is also important to ensure tops do not become too bulky. Overly bulky tops make harvest difficult due to tangling in the harvester (Ralph Oomen, Personal Communication). PCU may be able to provide a steadier supply of N and improve harvest efficiency while not causing tops to become too bulky.

Research needs and objectives. Current N management practices in processing carrot production can have negative impacts on the environment including contamination of surface and groundwater through runoff and leaching. Nitrogen supplied by top-dress of U+UI provides a large pool of soluble N at one time. The N that cannot be taken up by the carrot crop is left vulnerable to an unintended fate; it is either taken up by weeds, volatilized as ammonia, or is lost by leaching below the rooting zone of the carrot crop it was intended for. These unintended fates cost the grower money. The use of PCU may provide a more even supply of N for a longer period following application allowing for fewer applications

of N over the course of the season which could save the grower time and money on application costs. An estimated savings of \$25/ha for each tractor pass is possible (Stein, 2011). Although previous research has given growers information on optimal N rates and to split application over the season to achieve desired carrot yield it is unclear if PCU could better meet those needs. In addition, it is unclear what effects PCU might have on harvest efficiency though N effects on petiole strength, and on the accumulation of CRN. While others have shown that N fertilization can impact CRN it is not understood how PCU and late season N management effect concentration of nitrate in carrot roots. The following studies, conducted on-farm in collaboration with Michigan processing carrot producers, focused on improving knowledge of PCU, and its possible uses for improving N management. production systems. Chapter 2 presents results from two years of on-farm experiments evaluating full-season N management strategies that integrate PCU. Chapter 3 presents results from a one-year study evaluating the impact of late season N application strategies, including both PCU and foliar N applications. In all studies, the goal was to better understand the impact of N management on standard measurements of yield and quality, as well as potential tradeoffs associated with petiole strength and CRN accumulation.

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CHAPTER TWO: Effects of Nitrogen Fertilizer Material, Timing and Rate on Carrot Quality and Yield

Abstract

Nitrogen (N) fertilizer material rate and application timing in processing carrots (*Daucus carota* L.) are important for maintaining strong petioles that withstand top-pull mechanical harvest and for minimizing carrot root nitrate (CRN) accumulation. A 2-year field study was conducted in growers' fields in Oceana County, Michigan in 2013 and 2014 to evaluate tradeoffs associated with N management. Treatments consisted of 4 N rates (67, 101, 135, and 168 kg N/ha); three application systems (Grower Practice, Early PCU and Delayed PCU) and two N fertilizer materials (U+UI and PCU) arranged in randomized complete block design with four replications. Results showed that both rate and system had little detectable effect on petiole strength. In 2013 the Early PCU system had greater CRN than Grower Practice and there was higher accumulation of CRN at the highest N rate. In 2014, CRN was highest under Grower Practice at the highest N rate.

Introduction

Nitrogen management in carrots. In Michigan processing carrot (*Daucus carota* L.) production systems, growers typically top-dress urea (46N-0P-0K) treated with the urease inhibitor Agrotain[®] (U+UI) (Koch Agronomic Services, Wichita, KS, USA) to supply nitrogen during the growing season. While Agrotain[®] helps reduce N lost to volatilization as ammonia by urease inhibition, its activity lasts for 2-3 weeks (Steinke and Bauer, 2017). An alternative to soluble urea is poly-coated urea (PCU) fertilizer materials such as “Environmentally Smart Nitrogen” (ESN[®]) (42N-0P-0K) (Nutrien [formerly Agrium] Saskatoon, SK, Canada) which works by protecting the urea prill by encapsulation in a polymer shell. The polymer shell is permeable, allowing water to infiltrate and dissolve the urea, after which it is released through the membrane-like polymer shell over time (Golden et al., 2011).

Polymer-coated urea. While U+UI stabilizes N in the urea form, it does not extend N availability as long as other N protectors. The release pattern exhibited by controlled release materials such as PCU may improve the synchrony of N demand by the crop with N supply as it can still be releasing N 40 days after application (Golden et al., 2011). The release pattern of N from PCU is regulated by temperature where the rate of N release increases with temperature when moisture is not limiting (Gandeza et al., 1991). Similarly, carrot growth responds proportionally as temperature increases to a point, after which it declines (Finch-Savage et al., 2001). This suggests that PCU may be able to supply N to the carrot crop at a rate that better approximates the timing of carrot N consumption.

Nitrogen management and carrot quality. Nitrogen material, rate and timing may also impact carrot quality, including the proportion of defects that may be sensitive to fluctuations in N availability (e.g. cracks), and the accumulation of nitrate (NO_3^-) in carrot root tissue. A particularly important emerging concern for some processors is NO_3^- content in the carrot root (Gerber, personal communication). If NO_3^- levels are high enough in food they can have detrimental health effects on those that consume them (Santamaria, 2006). Warncke (1996) showed that nitrogen fertilizer applications late in the season resulted in higher carrot root NO_3^- (CRN) concentrations and did not increase root yield.

Similarly, Boskovic-Rakocevic et al. (2012) as well as Gajewski et al. (2009) observed that higher rates of N fertilization increased CRN. On the other hand, Gutezeit (1999) reported that CRN did not appear to be correlated with N fertilization. Such differences in fertilizer effects on CRN are likely due in part to other factors—including shade, cultivar and foliar disease—which are known to interact with N fertilization in determining CRN (Blanc et al., 1979). Conventional U+UI top-dress application can lead to peaks and valleys in plant available N, whereas, PCU provides N over a longer period of time (Golden, 2009). The elimination of the fluctuations in N may help maintain low or reduced NO_3^- content in carrot products. Also, PCU may allow for a reduction in the optimal N fertilizer rate and lead to fewer cracked carrot defects (Hartz et al., 2005). N management has also been shown to influence other quality parameters, including sugar levels, and compounds influencing flavor (Hochmuth et al., 1999) as well as Vitamin C content of roots (Boskovic-Rakocevic et al., 2012).

Economics of polymer-coated urea. The economic impact of PCU in carrots is not clear. Although PCU materials typically cost 13 to 22% more than U+UI, potential savings in N requirements and application costs through fewer tractor passes, coupled with improvements in crop quality or harvestable yield, may justify their use. In the past, the higher price of PCU over conventional soluble N sources was thought to outweigh the benefits it provides in many crops (Guertal, 2009). However, the work of Wilson et al. (2009), showed that, since prices have come down, PCU had similar net returns to split applications of soluble N in potato. Benefits have also been shown in other vegetable crops such as bell pepper where comparable yields to conventional split applications of N can be achieved using controlled release N materials applied before planting (Guertal, 2000).

Harvest efficiency. N management practices may also influence harvest efficiency through their effects on shoot growth and petiole strength. Petiole strength is an important factor in determining harvest efficiency for processing carrots, and is thought to be influenced by late season N availability (Makries and Warncke, 2013). In order to achieve maximum harvested yield, the carrot tops must be strong enough to withstand the abuse of top-pull harvest equipment. Carrot top biomass accumulation is often far more responsive to N fertilization than root biomass (Warncke, 1996; Westerveld et al., 2006).

Therefore, previous studies evaluating N rates in hand-harvested research plots may underestimate optimal rates given potential improvements in harvest efficiency and harvestable yield at higher N rates. This is analogous to the observation by Bounds et al. (2006), that optimal fungicide rates may be higher than suggested by previous studies, when the effect of reduced petiole health on harvest efficiency is ignored. Although strong tops are important for harvest efficiency, excessive top growth may create harvest and crop quality issues as well; overly bulky tops make harvest difficult due to tangling in the harvest equipment (Ralph Oomen, personal communication). It is quite evident that a delicate balance be achieved with respect to N management from the harvest efficiency angle. PCU may be able to provide a steady supply of N improving harvest efficiency while not causing tops to become too bulky.

Environmental impacts of nitrogen management. Controlled release N products may also be helpful for reducing N losses to the environment. Current N management practices in carrot production may contaminate surface and groundwater through runoff and leaching (Wang and Alva, 1996), as well as losses through volatilization and denitrification. Nitrogen supplied by top-dress of U+UI provides a large pool of soluble N at one time. This, coupled with the irrigation required to grow carrots on sandy soils, promotes leaching of N below rooting depth where it may be carried beyond to groundwater (Warncke, 1996). Use of PCU materials has been shown to reduce leaching of N (Alva, 1992). Therefore, the use of PCU could help protect against N losses due to leaching in carrots grown on sandy soils.

Objectives and hypotheses. The tradeoffs associated with PCU and N rate on carrot yield, quality and harvest-ability under Michigan production systems are unclear. Therefore, the primary objectives of our study were to determine the impact of N fertilizer material (U+UI vs PCU), rate and application timing on 1) carrot quality and yield; 2) petiole strength; and 3) CRN accumulation. We hypothesized that higher N rates would result in greater top growth and petiole strength, but would also increase accumulation of CRN. In addition, we hypothesized that PCU would result in a lower optimal N rate and improved carrot quality compared to standard grower practice.

Materials and Methods

Plot establishment. Field trials were conducted in 2013 and 2014 at two on-farm locations in Oceana County, Michigan to assess the effects of PCU on PC yield and quality compared with standard grower N management practices. In 2013 the trial was located at 43°45'18.05" N, 86°21'19.15" W on Spinks-Tekenink loamy fine sands where typical CEC is 9.4 meq/100g and organic matter is 1.4% (NRCS, 2018). In 2014 the trial was located at 43°44'53.03" N, 86°15'11.01" W on Pipestone fine sand. These soils typically have a CEC of 6.0 meq/100g and 0.8% organic matter (NRCS, 2018). Field preparation was accomplished by strip tilling into a standing cover of either winter wheat in 2013 or barley in 2014. The strip tiller was custom built by our grower collaborator, and consisted of a shank followed by a liquid fertilizer tube, berm forming disks, and 23 cm wide hydraulically driven rotary cultivator. During strip tillage 25 kg/ha N from urea ammonium nitrate (UAN) (28N-0P-0K) was injected behind the shank to a depth of approximately 15 cm below the carrot row across all plots.

Experimental treatments and schedule. In both years the experimental treatments consisted of combinations of four nitrogen rates (67, 101, 135, and 168 kg N/ha); three application systems (grower practice control, early PCU and delayed PCU) and two N fertilizer materials (U+UI and PCU [ESN]) arranged in randomized complete block design with four replications (Table 2.1). In addition, we included a low N control treatment that received only 25 kg N/ha from UAN during strip tillage. Plots measured 4.88 m by 9.14 m and included three beds of carrots, each with three carrot rows spaced 46 cm apart. Strip tillage and carrot (*cv. Canada*) planting occurred on 1 May 2013 and in 2014 strip tillage occurred on 28 Apr. followed by carrot planting (*cv. Canada*) on 4 May.

Field operations are summarized in Table 2.2. In the Early PCU system, approximately 27% of seasonal total N rate was broadcast applied as PCU just prior to strip tillage followed by two top-dress applications of U+UI in late-July/early-August and mid-August. In the Delayed PCU system, approximately 55% of the seasonal total N rate was top-dress applied as PCU approximately 30 days after planting followed by a top-dress of U+UI in mid-August. The Grower Practice treatments consisted of

Table 2.1: Explanation of treatments, 2013 and 2014.

System	Rate ^x	Nitrogen Fertilizer Application Timing									
		Timing 1 ^y		Timing 2		Timing 3		Timing 4		Timing 5	
		Material ^z	N Rate ^w	Material	N Rate	Material	N Rate	Material	N Rate	Material	N Rate
Grower Practice	67	UAN	25.0	N/A	0	U+UI	14.2	U+UI	14.2	U+UI	14.2
	101	UAN	25.0	N/A	0	U+UI	25.4	U+UI	25.4	U+UI	25.4
	135	UAN	25.0	N/A	0	U+UI	36.7	U+UI	36.7	U+UI	36.7
	168	UAN	25.0	N/A	0	U+UI	47.9	U+UI	47.9	U+UI	47.9
Early PCU	67	UAN PCU	25.0 16.8	N/A	0	N/A	0	U+UI	12.9	U+UI	12.9
	101	UAN PCU	25.0 28.0	N/A	0	N/A	0	U+UI	24.1	U+UI	24.1
	135	UAN PCU	25.0 39.2	N/A	0	N/A	0	U+UI	35.3	U+UI	35.3
	168	UAN PCU	25.0 50.4	N/A	0	N/A	0	U+UI	46.5	U+UI	46.5
Delayed PCU	67	UAN	25.0	PCU	33.6	N/A	0	N/A	0	U+UI	9.0
	101	UAN	25.0	PCU	56.0	N/A	0	N/A	0	U+UI	20.2
	135	UAN	25.0	PCU	78.5	N/A	0	N/A	0	U+UI	31.4
	168	UAN	25.0	PCU	100.9	N/A	0	N/A	0	U+UI	42.6
Low N	25	UAN	25.0	N/A	0	N/A	0	N/A	0	N/A	0

^zUAN: Urea Ammonium Nitrate (28N-0P-0K); PCU: (42N-0P-0K); U+UI: Urea + Agrotain (46N-0P-0K).

^yTiming 1: 28 Apr. 2013, 1 May 2014; Timing 2: 18 June 2013, 25 June 2014; Timing 3: 10 July 2013, 9 July 2014; Timing 4: 25 July 2013, 8 Aug. 2014; Timing 5: 20 Aug. 2013, 25 Aug 2014.

^xSeason total N rate may not add up from values in table due to rounding error when converting from lbs N/acre to kg N/ha.

^wAll N rates are expressed as kg N/ha.

Table 2.2: Schedule of main field operations and data collection events, 2013 and 2014.

Event	Date	
	2013	2014
Tillage & Starter N	28 Apr.	1 May
Early ESN treatment application	28 Apr.	1 May
Carrot planting	5 May	1 May
Soil sample	18 June	25 June
Delayed ESN treatment application	18 June	25 June
Soil sample	10 July	9 July
N top dress	10 July	9 July
Soil sample	25 July	8 Aug.
N top dress	25 July	8 Aug.
Soil Sample	20 Aug.	25 Aug.
N top dress	20 Aug.	25 Aug.
Carrot harvest	17 Oct. ^x	13 Oct.
Petiole strength sample	17 Oct. ^x	13 Oct.

^xReplicates 1-3 collected 17 Oct. 2014, Replicate 4 collected 22 Oct. 2013. Plots 110, 303 and 312 collected 29 Oct. 2013.

split applications of U+UI in early July, late July/early August, and mid to late August. All aspects of crop management not related to N management were performed by the grower cooperator following standard procedures (Bird et al., 2015; Zandstra, 2013).

Data collection. Soil samples were collected from 10-12 composite cores per plot to a depth of 20 cm in 2013 and 30 cm in 2014. A soil sample was collected in both years prior to tillage and N fertilizer application to establish baseline NO_3^- and ammonium (NH_4^+) levels. Additionally, soil samples were collected in each plot just prior to each top-dress N application. Soil NO_3^- and NH_4^+ system effects were not tested for 15 June 2013 because only the Early PCU system had established treatments at this time point. Dried soil samples were extracted with 1 M KCl for NO_3^- and NH_4^+ following Gelderman and Beegle (1998), and analyzed by cadmium reduction on a Lachatt Quickchem flow-through colorimetric analyzer (Hach Company, Loveland, CO, USA) at the Michigan State University Soil and Plant Nutrient Laboratory.

Carrot yield and quality was measured in 2013 on reps 1-3 and rep 4 on 17 and 22 Oct. respectively and on 13 Oct. 2014. Carrots were harvested from 4.57 m and 6.1 m in 2013 and 2014 respectively. Count data were collected from the harvested area to measure final carrot stand. Carrot roots were separated into categories (defect-free (marketable), cracked, forked, nub, or undersized) then counted and weighed. Following Brainard and Noyes (2012), carrots were considered not marketable if cracks exceeded 2.5 cm in length, forks exceeded two per root, end of root was flattened or nub shaped, and undersized if root diameter at the shoulder was less than 3.2 cm. In addition, a subsample of 5-10 intact carrot plants (root and shoot) were carefully excavated for subsequent analysis of petiole strength, Total Kjeldahl Nitrogen, and CRN.

Petiole strength of five or ten subsampled carrot plants from each plot was measured with a Shimpo FGV-100XY force gauge (Shimpo, Wilmington, NC, USA) to determine the amount of force required to separate the petioles from the crown of the plant. To accomplish this measurement, individual carrots roots were held stationary in a vice. The force gauge was then clamped to petioles just above the root crown and an even force was applied until the petioles broke. The peak force required to break the

petioles was recorded. Carrot shoot biomass was measured in 2013 by drying the shoots of the petiole strength subsample. In 2014, all of the shoots from the harvested area were collected and dried. In both years, the shoot tissue was dried at 60° C until a stable dry weight was reached.

Carrot root nitrate was determined by taking a 2.5 cm segment from the middle of the carrot roots from the petiole strength subsample. The sections were then diced, dried at 60° C and ground to pass through a 1 mm mesh. The ground carrot root tissue was extracted with 1 M potassium chloride in water following a method adapted from Binford et al. 1990. The extracts were tested for nitrate concentration at the Michigan State University Soil and Plant Nutrient Laboratory.

Total nitrogen content of carrot roots and shoots was determined by micro Kjeldahl digestion (TKN) and colormetric analysis with a Lachat flow-through auto-analyzer (Nelson and Sommers, 1973; Bremner, 1996). Tissue was collected at harvest time for TKN. Carrot taproot tissue from ten random defect-free carrots was subsampled from a 5 cm section collected from approximately the midpoint of the taproot. Both the root and shoot tissues were dried at 60° C and then ground to pass through a 1 mm screen prior to TKN digestion. The shoot tissue was a random subsample of the carrot tops from the harvested area.

Statistical analysis. Analysis of the effects of N source, rate, and timing and their interactions on yield, quality, petiole strength, soil inorganic N, CRN, and N content of plant tissue were conducted in SAS (SAS Institute, 2012) using the PROC MIXED procedure. Rate and system were defined as fixed effects and replication was designated as a random effect. Normality assumptions were tested on residuals in SAS using the UNIVARIATE procedure Shapiro-Wilk ($P \leq 0.05$). To improve normality and equal variance assumptions, data for many responses were transformed using either natural log or square root transformations (Table 2.3). Where ANOVA indicated a significant F value ($P < 0.05$) means were separated using Fisher's protected LSD. When no yield response to N rate occurred Dunnett's test was performed to assess site responsiveness to N treatments relative to the lowest N treatment.

Table 2.3: Data transformations to improve normality and equal variance assumptions.

Variable	Year	Transformation Applied
Inorganic Soil Nitrogen		
18 June Ammonium	2013	Natural Log
10 July Ammonium	2013	Natural Log
25 July Ammonium	2013	Natural Log
20 Aug. Nitrate	2013	Natural Log
6 Aug. Nitrate	2014	Natural Log
6 Aug. Ammonium	2014	Natural Log
25 Aug. Nitrate	2014	Natural Log
Yield and Quality		
Total Not Marketable	2013	Square Root
Forked Weight	2013	Square Root
Nub Weight	2013	Natural Log
Small Weight	2013	Square Root
Cracked Weight	2013	Square Root
Total Not Marketable	2014	Square Root
Forked Weight	2014	Square Root
Nub Weight	2014	Square Root
Cracked Weight	2014	Natural Log
Petiole Strength		
Petiole Strength	2014	Natural Log
Carrot Shoot Biomass	2014	Natural Log
Total Kjeldahl Nitrogen		
Shoot	2014	Square Root
Carrot Root Nitrate		
Root Nitrate	2013	Square Root
Root Nitrate	2014	Square Root

Results and Discussion

Weather. Temperature and rainfall conditions varied considerably across years and months (Table 2.4). Monthly mean temperatures were similar in 2013 and 2014, with the exception of the first few weeks of October, during which the mean temperature in 2014 was 4.1°C lower than in 2013. Rainfall was more than 50% higher in May and June of 2014 than in 2013 leading to approximately 23% more rainfall in 2014.

Soil inorganic N 2013. Pre-fertilization soil inorganic N concentrations in 2013 were 1.16 mg·kg⁻¹ NO₃⁻ and 3.27 mg·kg⁻¹ NH₄⁺. Subsequent soil NO₃⁻ and NH₄⁺ concentrations were affected by rate, system and their interactions at several sampling dates in 2013 (Table 2.5). At the first 3 sampling dates, soil NO₃⁻ generally increased with N rate, but these differences had dissipated by October. The effect of system on soil NO₃⁻ was significant on 10 July, and 17 Oct. of 2013, with higher soil NO₃⁻ observed for both PCU systems on 10 July, and for the Delayed PCU system on 17 Oct. The effect of rate on soil NH₄⁺ varied by system on 10 July, and soil NO₃⁻ on 20 Aug. 2013, but these effects were small (data not shown) and most likely due to differing cumulative amounts of N fertilizer application for a given rate across systems at those sample timings (Table 2.1).

Soil inorganic N 2014. Pre-fertilization soil inorganic N concentrations in 2014 were 1.85 mg/kg NO₃⁻ and 1.88 mg/kg NH₄⁺. Subsequent soil NO₃⁻ and NH₄⁺ concentrations were affected by rate and system at several sampling dates, but the effect of rate did not vary by system (interaction NS) (Table 2.6). Soil NO₃⁻, for the first four sampling dates of 2014, generally increased with N rate, but at the harvest date this rate effect was no longer detectable. In contrast, rate did not affect soil NH₄⁺ concentration at any sampling date. There was a system effect on 9 July 2014 where the Early PCU system had higher soil NO₃⁻ and NH₄⁺ levels. A system effect was also detected on 25 Aug. where both the Grower Practice and Early PCU systems had higher soil NO₃⁻. No other time point had a detectable system effect for either NO₃⁻ or NH₄⁺.

Table 2.4: Average temperature and monthly cumulative rainfall, 2013 and 2014.

Month	Temperature (°C)		Rainfall (mm)	
	2013	2014	2013	2014
May	14.4	15.0	87.36	112.00
June	18.2	19.2	38.61	129.00
July	20.5	18.1	62.74	33.80
August	19.2	19.8	56.88	52.80
September	16.0	15.4	60.46	65.80
October ^x	13.5	9.4	42.18	59.20

^x2013 October 1st-17th, 2014 October 1st-13th.

Table 2.5: N rate and system effects on soil inorganic nitrogen (sample depth 0-20 cm), 2013.

	18 June 2013					10 July 2013					25 July 2013					
	NO ₃ ⁻ -N			NH ₄ ⁺ -N ^w		NO ₃ ⁻ -N			NH ₄ ⁺ -N ^w		NO ₃ ⁻ -N			NH ₄ ⁺ -N ^w		
Rate main effect^z	-----mg/kg-----															
67	9.5	(0.9)	B ^x	4.1	(0.4)	13.5	(1.5)	B	1.2	(0.1)	6.3	(0.6)	C	1.1	(0.1)	B
101	11.6	(2.0)	AB	3.8	(0.2)	14.3	(1.4)	B	1.5	(0.3)	8.0	(0.5)	BC	1.5	(0.2)	AB
135	14.5	(0.8)	A	3.9	(0.2)	18.1	(2.1)	A	1.6	(0.3)	10.0	(0.7)	B	1.3	(0.1)	AB
168	17.1	(3.2)	AB	3.6	(0.1)	18.9	(2.1)	A	1.9	(0.4)	12.9	(0.9)	A	1.4	(0.1)	A
Low N^y																
25	7.7	(0.7)		3.8	(0.2)	9.7	(1.4)		1.1	(0.1)	3.6	(0.3)		1.4	(0.1)	
System main effect																
Grower Practice	---N/A---			---N/A---		9.2	(0.5)	B	1.0	(0.0)	8.7	(0.8)		1.2	(0.1)	
Early PCU	13.7	(1.1)		4.0	(0.2)	19.8	(1.3)	A	1.2	(0.1)	9.0	(1.0)		1.4	(0.2)	
Delayed PCU	---N/A---			---N/A---		19.6	(1.2)	A	2.5	(0.3)	10.1	(0.7)		1.4	(0.1)	
ANOVA	-----Significance (P-value)-----															
Rate	0.0456			0.8807		0.0001			0.0187		<.0001			0.0254		
System	---N/A---			---N/A---		<.0001			<.0001		0.2881			0.5606		
System X Rate	---N/A---			---N/A---		0.1618			0.0086		0.8089			0.1158		

^zRates are expressed as kg N/ha.

^yLow N was excluded from ANOVA.

^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha=0.05$.

^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

Table 2.5: (Cont'd).

	20 Aug. 2013		17 Oct. 2013	
	NO ₃ ⁻ -N ^w	NH ₄ ⁺ -N	NO ₃ ⁻ -N	NH ₄ ⁺ -N
Rate main effect^z	-----mg/kg-----			
67	1.5 (0.1)	2.2 (0.1)	1.0 (0.1)	3.2 (0.2) AB
101	1.6 (0.1)	2.3 (0.1)	1.0 (0.1)	3.6 (0.2) A
135	2.8 (0.5)	2.3 (0.1)	1.0 (0.1)	3.0 (0.1) B
168	4.2 (0.6)	2.9 (0.6)	1.1 (0.1)	3.4 (0.2) AB
Low N^y				
25	1.3 (0.1)	2.2 (0.1)	1.0 (0.2)	3.3 (0.3)
System main effect				
Grower Practice	3.3 (0.6)	2.2 (0.1)	1.0 (0.1) B	3.2 (0.1)
Early PCU	2.2 (0.3)	2.3 (0.1)	1.0 (0.1) B	3.3 (0.2)
Delayed PCU	2.0 (0.2)	2.8 (0.5)	1.1 (0.1) A	3.5 (0.2)
ANOVA	-----Significance (P-value)-----			
Rate	< 0.0001	0.7376	0.2930	0.0500
System	0.0616	0.3262	0.0311	0.2047
System X Rate	0.0330	0.2183	0.7650	0.1632

^zRates are expressed as kg N/ha.^yLow N was excluded from ANOVA.^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha = 0.05$.^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation

Table 2.6: N rate and system effects on inorganic soil nitrogen (sample depth 0-30 cm), 2014.

	25 June 2014				9 July 2014				6 Aug. 2014						
	NO ₃ ⁻ -N		NH ₄ ⁺ -N		NO ₃ ⁻ -N		NH ₄ ⁺ -N		NO ₃ ⁻ -N ^w		NH ₄ ⁺ -N ^w				
Rate main effect ^z	-----mg/kg-----														
67	11.3	(0.5)	B ^x	2.9	(0.1)	8.5	(1.0)	B	4.8	(0.2)	2.3	(0.4)	C	1.5	(0.1)
101	14.2	(1.0)	B	3.0	(0.2)	8.2	(0.6)	B	5.0	(0.3)	3.3	(0.7)	BC	1.2	(0.1)
135	15.4	(2.2)	AB	3.6	(0.6)	10.8	(1.5)	AB	5.6	(0.4)	4.6	(0.7)	AB	1.3	(0.1)
168	21.0	(2.8)	A	3.3	(0.1)	12.7	(1.7)	A	5.1	(0.5)	6.6	(1.9)	A	1.6	(0.1)
Low N ^y															
25	8.2	(0.9)		3.0	(0.3)	5.6	(0.6)		4.5	(0.2)	0.7	(0.1)		1.2	(0.1)
System main effect															
Grower Practice	---N/A---		---N/A---		---N/A---		---N/A---		4.6 (1.5)				1.4 (0.1)		
Early PCU	15.5	(1.2)		3.2	(0.3)	11.8	(1.0)	A	4.5	(0.2)	B	3.5	(0.6)		1.4 (0.1)
Delayed PCU	---N/A---		---N/A---		8.3	(0.7)	B	5.7	(0.2)	A	4.5	(0.6)		1.4	(0.1)
ANOVA	-----Significance (P-value)-----														
Rate	0.0246		0.5901		0.0401		0.2651		0.0114		0.0928				
System	---N/A---		---N/A---		0.0041		0.0004		0.2620		0.8091				
System X Rate	---N/A---		---N/A---		0.2482		0.8034		0.5703		0.7633				

^zRates are expressed as kg N/ha.

^yLow N was excluded from ANOVA.

^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha=0.05$.

^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

Table 2.6: (Cont'd).

	25 Aug. 2014						13 Oct. 2014			
	NO ₃ ⁻ -N ^w			NH ₄ ⁺ -N			NO ₃ ⁻ -N ^w		NH ₄ ⁺ -N	
Rate main effect^z	-----mg/kg-----									
67	0.6	(0.1)	C	1.0	(0.1)		0.6	(0.1)		1.5 (0.4)
101	1.3	(0.5)	BC	0.9	(0.1)		0.5	(0.1)		1.0 (0.1)
135	1.6	(0.3)	B	1.0	(0.1)		0.7	(0.1)		1.0 (0.1)
168	4.1	(1.0)	A	1.0	(0.1)		1.0	(0.3)		1.0 (0.2)
Low N^y										
25	0.5	(0.0)		0.9	(0.1)		0.3	(0.1)		1.5 (0.6)
System main effect										
Grower Practice	2.8	(0.9)	A	0.9	(0.0)		0.8	(0.2)		1.2 (0.2)
Early PCU	1.9	(0.4)	A	1.0	(0.1)		0.8	(0.1)		1.0 (0.1)
Delayed PCU	1.0	(0.3)	B	1.0	(0.1)		0.5	(0.2)		1.1 (0.1)
ANOVA	-----Significance (P-value)-----									
Rate	< 0.0001			0.1232			0.1341		0.4057	
System	0.0076			0.1022			0.5001		0.6887	
System X Rate	0.3725			0.6885			0.9950		0.7334	

^zRates are expressed as kg N/ha.

^yLow N was excluded from ANOVA.

^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha = 0.05$.

^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

In both years, rate had a strong effect on soil inorganic NO_3^- through summer, but rate effects had dissipated by the harvest date. Dissipation over time in differences in soil N due to rate have been observed in other studies (Makries and Warncke, 2013; Warncke, 1996) and may be due to greater N use by the larger carrot crop later in the season as well as by reduced mineralization of N as soil temperatures decline. Contrary to expectations, few system effects on soil N were detected in either year, and those that did occur could be explained largely by the difference in cumulative N fertilizer applied at the time of sampling.

Carrot stand, yield and quality. No differences in carrot stand at harvest were detected in either 2013 or 2014 (Table 2.7). In 2013, no significant effects of rate, system or their interactions on yield or quality were detected (Table 2.8). In 2014, both total yield and marketable yield categories were affected by rate, but not by system or rate by system interactions. Total and marketable yields were greater at the 135 and 168 kg N/ha rates in 2014. In 2014, total not marketable weight also increased with N rate, but this was likely due to larger carrots at higher N rates, rather than a higher proportion of defective carrots. There were no other detectable effects of rate or system or their interactions on specific categories (e.g. forks, nubs and cracks) of carrot quality in either 2013 or 2014.

N management rate and system had surprisingly little effect on yield or quality, especially in 2013. This supports findings by Warncke (1996), and Westerveld (2006) that carrot root biomass is not highly responsive to N fertilization. However, given the level of variability in 2013, our statistical power may have been too low to detect differences in yield due to N rate or system. In addition, the 2013 site overall was relatively unresponsive to our N treatments. This may have been due to the higher levels of soil organic matter at the 2013 site (approximately 1.4%) compared to the 2014 site (approximately 0.8%), which may have contributed substantial N to the carrot crop through mineralization. Alternatively, NO_3^- in the irrigation water, which we did not measure, may have contributed to lack of N response in 2013; previous studies conducted in Michigan have shown that irrigation water may supply substantial N in some cases (Makries and Warncke, 2013).

Petiole breaking strength and carrot shoot biomass. We did not detect significant rate or system effects on petiole strength in either year (Table 2.9). The effect of rate on petiole strength was marginally significant in 2013 ($P = 0.0802$) where petiole strength may have been higher at the highest N rate. No significant rate effect on petiole breaking strength was detected in 2014.

Table 2.7: N rate and system effects on final carrot stand, 2013 and 2014.

	Carrot Stand at Harvest	
	2013	2014
Rate main effect^z	-----Thousands/ha-----	
67	114 (5)	108 (7)
101	119 (4)	100 (3)
135	105 (6)	105 (8)
168	121 (3)	104 (6)
Low N^y		
25	119 (6)	99 (8)
System main effect		
Grower Practice	113 (5)	101 (6)
Early PCU	112 (4)	106 (6)
Delayed PCU	119 (4)	105 (5)
ANOVA	-----Significance (P-value)-----	
Rate	0.1235	0.8245
System	0.5001	0.8194
System X Rate	0.5123	0.2086

^zRates are expressed as kg N/ha.

^yLow N was excluded from ANOVA.

Table 2.8: N rate and system effects on carrot yield and quality, 2013 and 2014.

	Total Weight					Marketable Weight					Total Not Marketable Weight				
	2013		2014			2013		2014			2013 ^w		2014 ^w		
Rate main effect ^z	-----Mg/ha-----														
67	98.5	(3.4)	77.1	(4.2)	B ^x	92.1	(3.2)	75.7	(4.1)	B	7.6	(2.1)	1.4	(0.4)	B
101	106.7	(3.5)	78.4	(3.9)	B	99.3	(3.7)	75.0	(3.5)	B	7.2	(1.1)	3.4	(1.2)	AB
135	105.3	(2.2)	90.4	(4.3)	A	97.6	(3.0)	85.6	(4.0)	A	8.1	(1.5)	4.8	(1.0)	A
168	104.6	(2.7)	90.4	(2.8)	A	97.5	(3.5)	86.4	(2.9)	A	7.8	(2.1)	4.0	(1.3)	A
Low N ^y															
25	95.3	(2.1)	61.1	(5.3)		88.3	(3.1)	59.8	(5.2)		6.7	(3.6)	1.3	(0.4)	
System main effect															
Grower Practice	106.2	(2.8)	83.3	(3.8)		99.4	(3.1)	78.8	(3.4)		7.1	(1.1)	4.5	(1.2)	
Early PCU	100.1	(2.2)	85.5	(4.6)		93.1	(2.9)	83.1	(4.4)		8.0	(1.8)	2.4	(0.5)	
Delayed PCU	105.0	(2.8)	83.5	(2.3)		97.4	(2.6)	80.1	(2.1)		8.0	(1.5)	3.3	(0.9)	
ANOVA	-----Significance (P-value)-----														
Rate	0.1265		0.0134			0.2939		0.0380			0.8920		0.0484		
System	0.1352		0.8539			0.1819		0.6923			0.8973		0.3551		
System X Rate	0.8439		0.4386			0.1819		0.2833			0.3077		0.1335		

^zRates are expressed as kg N/ha.

^yLow N was excluded from ANOVA.

^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha=0.05$.

^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

Table 2.8: (Cont'd).

	Forked Weight		Nub Weight	
	2013 ^w	2014 ^w	2013 ^w	2014 ^w
Rate main effect^z	-----Mg/ha-----			
67	3.0 (0.9)	1.1 (0.4)	1.6 (0.8)	0.1 (0.1)
101	4.4 (0.9)	2.1 (0.6)	0.3 (0.1)	0.2 (0.4)
135	3.5 (0.8)	2.9 (0.9)	0.6 (0.3)	0.3 (0.5)
168	3.2 (0.8)	2.2 (0.8)	1.1 (0.6)	0.2 (0.3)
Low N^y				
25	5.6 (3.1)	0.7 (0.3)	0.2 (0.2)	0.3 (0.2)
System main effect				
Grower Practice	3.3 (0.7)	3.0 (0.8)	0.6 (0.3)	0.2 (0.3)
Early PCU	3.6 (0.9)	1.6 (0.4)	1.3 (0.5)	0.1 (0.2)
Delayed PCU	3.6 (0.6)	1.6 (0.4)	0.8 (0.5)	0.3 (0.4)
ANOVA	-----Significance (P-value)-----			
Rate	0.5485	0.3672	0.5063	0.2844
System	0.9314	0.4794	0.6414	0.1998
System X Rate	0.3089	0.3123	0.2567	0.7468

^zRates are expressed as kg N/ha.^yLow N was excluded from ANOVA.^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha=0.05$.^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

Table 2.8: (Cont'd).

	Cracked Weight				Undersized Weight			
	2013 ^w		2014 ^w		2013 ^w		2014	
Rate main effect^z	-----Mg/ha-----							
67	1.4	(0.5)	0.0	(0.0)	0.3	(0.1)	0.2	(0.1)
101	2.2	(0.6)	0.5	(0.3)	0.5	(0.2)	0.2	(0.0)
135	3.3	(1.1)	0.8	(0.4)	0.2	(0.1)	0.1	(0.0)
168	2.5	(0.6)	1.1	(0.7)	0.4	(0.1)	0.1	(0.0)
Low N^y								
25	0.6	(0.6)	0.0	(0.0)	0.2	(0.2)	0.4	(0.1)
System main effect								
Grower Practice	2.5	(0.9)	0.8	(0.5)	0.6	(0.3)	0.1	(0.0)
Early PCU	1.8	(0.5)	0.4	(0.3)	1.3	(0.5)	0.2	(0.0)
Delayed PCU	2.7	(0.6)	0.6	(0.3)	0.8	(0.5)	0.2	(0.0)
ANOVA	-----Significance (P-value)-----							
Rate	0.4777		0.3611		0.2525		0.3158	
System	0.5732		0.851		0.2734		0.7390	
System X Rate	0.6728		0.383		0.5790		0.3191	

^zRates are expressed as kg N/ha.^yLow N was excluded from ANOVA.^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha=0.05$.^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

Table 2.9: N rate and system effects on petiole breaking strength and dry shoot biomass, 2013 and 2014.

	Petiole Strength		Shoot Biomass	
	2013	2014 ^w	2013	2014 ^w
Rate main effect^z	-----Newton-----		-----g/plant-----	
67	158 (11)	175 (7)	13.0 (0.9)	9.4 (0.7) C
101	170 (6)	197 (21)	13.7 (0.6)	11.3 (0.7) BC
135	172 (11)	200 (16)	13.3 (0.6)	14.2 (2.1) AB
168	191 (6)	201 (19)	14.2 (0.6)	15.1 (1.7) A
Low N^y				
25	145 (22)	147 (19)	10.6 (0.8)	7.0 (0.8)
System main effect				
Grower Practice	165 (7)	191 (15)	12.9 (0.5)	12.8 (1.5)
Early PCU	179 (8)	200 (16)	13.8 (0.6)	12.3 (0.6)
Delayed PCU	175 (10)	188 (12)	13.9 (0.7)	12.4 (1.7)
ANOVA	-----Significance (P-value)-----			
Rate	0.0802	0.5258	0.4218	0.0036
System	0.5087	0.6866	0.5238	0.7859
System X Rate	0.7731	0.3370	0.7138	0.4551

^zRates are expressed as kg N/ha.

^yLow N was excluded from ANOVA.

^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha = 0.05$.

^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

The effect of N rate on carrot shoot biomass was not detected in 2013 (Table 2.9). In contrast, 2014 there was a significant rate effect on carrot shoot biomass with greater biomass occurring at higher N rates. However, no system effect on carrot shoot biomass was detected in either year.

Our hypothesis that higher N rates would result in greater shoot biomass and petiole strength, and therefore reduced risk of yield losses was not clearly supported by our data. However, it should be noted that our method of determining petiole strength was highly variable, resulting in low power to detect differences. In addition, the forces measured using our method may not be well-correlated with forces applied by a carrot harvester, which simultaneously digs and pulls carrots. More research is needed to measure forces applied by carrot harvesters, and to identify methods for quantifying relevant measures of resistance to those forces.

TKN carrot tissue. In 2013 and 2014, both root and shoot TKN % N increased proportionally with N rate (Table 2.10). In 2013 shoot TKN % N was more responsive to Early PCU and Delayed PCU systems than the Grower Practice system, while we did not detect an effect of system on carrot root TKN % N. In 2014, root TKN % N was higher in the Grower Practice system than either of the PCU systems; however, in this year we did not detect any system effects on the carrot shoot TKN % N.

Carrot root nitrate. In 2013, CRN was affected by both rate and system, but not by their interaction (Table 2.11). In particular, CRN was more than 3-fold higher at the 168 kg N/ha rate, compared to the 67 kg N/ha rate. CRN was more than twice as high in the Delayed PCU system compared to Grower Practice in 2013.

Table 2.10: N rate and system effects on Total Kjeldahl nitrogen (TKN) of carrot tissue at harvest, 2013 and 2014.

	Root			Shoot ^w			Root			Shoot		
	2013						2014					
Rate main effect ^z	-----TKN % N-----											
67	0.87	(0.87)	C ^x	1.11	(0.05)	C	0.84	(0.02)	C	1.19	(0.04)	C
101	1.00	(1.00)	B	1.18	(0.05)	C	0.99	(0.04)	B	1.38	(0.05)	B
135	1.07	(1.07)	B	1.31	(0.04)	B	1.13	(0.04)	A	1.32	(0.14)	BC
168	1.21	(1.21)	A	1.43	(0.05)	A	1.16	(0.04)	A	1.67	(0.06)	A
Low N ^y												
25	0.69	(0.02)		0.97	(0.03)		0.61	(0.03)		0.97	(0.05)	
System main effect												
Grower Practice	1.03	(0.04)		1.17	(0.05)	B	1.09	(0.05)	A	1.43	(0.06)	
Early PCU	1.04	(0.04)		1.26	(0.05)	A	1.00	(0.03)	B	1.43	(0.07)	
Delayed PCU	1.05	(0.04)		1.34	(0.04)	A	0.99	(0.05)	B	1.31	(0.10)	
ANOVA	-----Significance (P-value)-----											
Rate	<.0001			<.0001			<.0001			0.0002		
System	0.8946			0.001			0.0296			0.4607		
System X Rate	0.6817			0.7327			0.2888			0.8926		

^zRates are expressed as kg N/ha.

^yLow N was excluded from ANOVA.

^xMeans not connected by the same letter within the same group in a column are significantly different $\alpha=0.05$.

^wAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

Table 2.11: N rate and system effects on carrot root nitrate by 1M KCl extraction, 2013.

	Root Nitrate ^v		
Rate main effect^z	-----mg/kg ^x -----		
67	112	(75)	B ^w
101	90	(14)	B
135	144	(44)	B
168	378	(81)	A
Low N^y	---N/A---		
25			
System main effect			
Grower Practice	96	(28)	B
Early PCU	186	(62)	AB
Delayed PCU	261	(70)	A
ANOVA	-Significance (P-value)-		
Rate	0.0006		
System	0.047		
System X Rate	0.531		

^zRates are expressed as Kg N/ha.

^xBased on dry carrot tissue.

^yLow N was not analyzed.

^wMeans not connected by the same letter within the same group in a column are significantly different $\alpha = 0.05$.

^vAlthough analysis was conducted on transformed data (see Table 2.3), means and standard errors of non-transformed data are provided for ease of interpretation.

In 2014, the effect of N rate on CRN varied with system (significant rate by system interaction; $P=0.005$). In particular, at the 168 kg/ha N rate, CRN accumulation was higher in the Grower Practice system compared to both the Early and Delayed PCU treatments (Figure 1).

Our results confirm the hypothesis that higher N rates can result in accumulation of both CRN (Table 2.10; 2013), and TKN (Table 2.9) in carrot roots, and that the extent of CRN accumulation sometimes depends on the timing and form of N (Table 2.11; Fig 2.1). It is interesting to note that the effects of system on CRN accumulation were different in 2013 and 2014. We speculate that differences in rainfall patterns may partially account for those differences. In particular, wetter conditions in May and June 2014 likely lead to increased N leaching which contributed to N-loss conditions that could have negatively impacted the PCU systems where a much greater proportion of seasonal N was applied early (Tables 2.1 and 2.4).

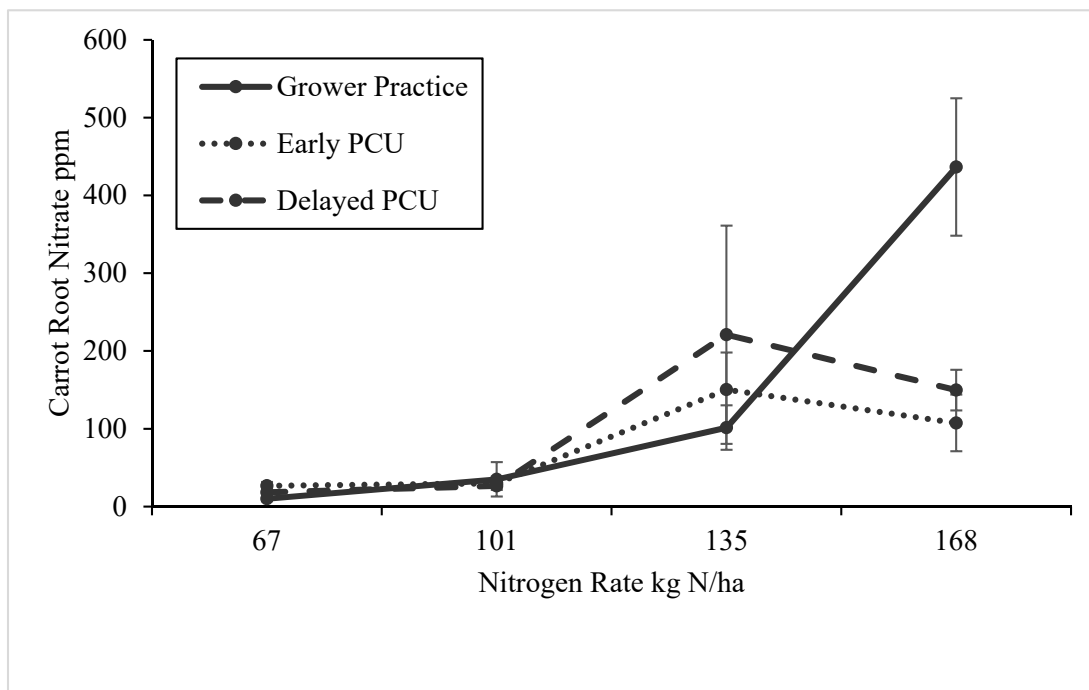


Figure 2.1: N rate and system effects on carrot root nitrate (CRN), 2014. The grower practice had significantly higher CRN compared to the other systems at the 168 kg N/ha rate ($P=0.005$).

Summary and Conclusion

No system effects were detected on yield, quality or petiole strength. While this result suggests minimal benefits of PCU in carrot production, it is important to note that both Early PCU and Delayed PCU could eliminate the need for one or more top-dress tractor passes, thereby saving the grower time. Both PCU systems entailed one fewer tractor pass than the Grower Practice system, which resulted in a savings of approximately \$25/ha (Stein, 2011). This savings partially offsets the additional cost of PCU which typically costs \$0.55 to \$0.66/kg N more than U+UI. For example, at the 101 kg N/ha rate, assuming an additional cost for PCU of \$0.60/kg N, the net additional cost would be approximately \$36/ha.

The practical significance of our observations regarding petiole strength response to N rate is unclear. Although we observed a marginally significant ($P=0.08$) increase in petiole strength of over 30% from the lowest to the highest N rate in 2013, it is unclear whether this improvement would have resulted in greater harvest efficiency. In order to better understand the effect of N fertilizer material and N rate on petiole strength, testing methodology should be improved to reduce variability, and improve our statistical power to detect differences that may have important economic implications. Additionally, the relationship between laboratory measurements and field top-pull harvest efficacy needs to be better quantified before definitive conclusions can be drawn.

The lack of rate and system effects on carrot yield in 2013 may be partly explained by relatively high residual soil N availability. In contrast, carrot yield increased with rate up to the 135 kg/ha rate in 2014. The rate response in 2014 (Table 2.8) coupled with the savings of a tractor pass in the PCU systems (Table 2.1) may make these systems more economically attractive on N responsive sites.

Rate effects on CRN largely responded as expected and were consistent with previous studies (e.g. Boskovic-Rakocevic et al., 2012; Gajewski et al., 2009) demonstrating increased CRN at higher N rates. However, the absolute level of CRN varied considerably across studies. In our study, the highest

observed CRN level was approximately 440 ppm on a dry weight basis, or only approximately 44 ppm on a fresh weight basis, which is below the typical range of 50 to 500 ppm reported at high rates of N application in other studies (Gajewski et al, 2009). The highest CRN concentrations observed in our study appear to be below the threshold considered detrimental to human health. However, it is important to note that measurement of CRN on dry carrot tissue with our extraction method may not be directly comparable to the fresh tissue measurements by which thresholds for CRN are established. System effects on CRN differed between years which may indicate that factors not controlled had an influence on their effects. It is possible that N-loss conditions due to higher rainfall in 2014 may have contributed to differing system responses between the two years (Table 2.4). In particular, lower CRN in the PCU systems at the highest N rate compared to the Grower Practice system may have been due in part to greater leaching in the PCU systems where a greater proportion of the seasonal N had been applied prior to the higher rainfall in 2014 (Tables 2.1 and 2.4). More work is needed to determine how N fertilizer material and timing affect CRN, and how these factors interact with other biotic and abiotic factors to determine CRN. Perhaps late-season N application strategies matter more than early season N management for minimizing CRN. Further research is needed to evaluate the effects of N material and rates late in the season.

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LITERATURE CITED

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CHAPTER THREE: Late-Season Nitrogen Application Effects on Nitrate Accumulation and Petiole Strength in Processing Carrots

Abstract

Maximum yield from mechanical harvest of carrot (*Daucus carota L*) relies on adequate late-season N to maintain petiole strength. However, excessive late season N may result in unacceptable accumulation of nitrates in carrot roots. To better understand these tradeoffs, the effects of late season N material and rate on carrot petiole strength, carrot yield, and carrot root nitrate (CRN) were examined in two field studies. In the first study, three systems were evaluated: 1) a single application of PCU (Late PCU); 2) a single application of U+UI (Late U+UI); and 3) four split applications of foliar applied UAN (Late Foliar). The second study evaluated the impact of four late-season rates of U+UI: 0, 22.4, 44.8, and 67.3 kg N/ha. In the first study, no system effects were detected on any parameters measured except for CRN where the Late Foliar system had the lowest CRN (at $P=0.0670$). The second study showed that CRN and shoot biomass were generally higher at the higher late-season N rates, but this did not translate into detectably greater petiole strength. Contrary to expectations, high late season N rates resulted in a marginally significant ($P=0.07$) increase in yield.

Introduction

Late-season nitrogen management. Nitrogen (N) management in carrots is important not only for its direct impact on yield, but also for its less direct effects on carrot quality and petiole strength. In processing carrot production, late-season applications of nitrogen are perceived by growers as important for maintaining healthy shoots necessary for efficient harvest. On the other hand, excessive N applications during this time may contribute to losses of nitrogen to the environment as well as nitrate accumulation in roots (Warncke, 1996), a concern particularly for carrots destined for the baby food market. The factors influencing these tradeoffs including the rate, timing, and form of N sources are poorly understood.

Maintenance of strong shoots is important late in the season for processing carrot production because growers in Michigan largely depend on top-pull harvest technology. In fact, the main economic impact of poor carrot shoot health late in the season is reduced efficiency of top pull harvest due to weak carrot petioles (Makries and Warncke, 2013). Several factors may influence petiole strength including foliar disease and N availability.

Carrot leaf blight (LB) caused by *Alternaria* and *Cercospora* is a major concern in top-pull harvested carrots due to both the direct negative effects of foliar disease on photosynthesis and carrot yield, and the indirect effect due to losses from carrot top breakage during harvest (Bounds et al., 2006; Rogers and Stevenson, 2006). Although they did not formally measure petiole strength, Bounds et al. (2006) found that as petiole health (rated visually) declined mechanical harvester efficiency also declined.

Harvest efficiency. Nitrogen management can impact petiole strength both directly, through impacts on shoot growth, and indirectly, via interactions with foliar diseases. The direct effect of N on shoot biomass has been well documented in various studies. For example, Warncke (1996) found that higher N rates resulted in greater shoot growth. Likewise, Westerveld et al. (2005; 2008) found that higher N rates, resulted in healthier tops and greater number of leaves per plant. Nitrogen management can also indirectly influence petiole strength through interactions with foliar diseases. For example, Westerveld et al. (2008) showed that higher N rates were inversely correlated with severity of foliar diseases. Under N

limiting conditions carrots were more susceptible to the both *Alternaria* and *Cercospora* (Westerveld, 2005), which are likely to contribute to weaker petioles and reduced harvestability (Bounds et al. 2006; Rogers and Stevenson, 2006).

Late-season nitrogen tradeoffs. At first, it might appear that simply adding more nitrogen later in the season would be an easy solution to help reduce foliar disease and increase mechanical harvest efficiency however, too much N late in the season can lead to elevated root nitrate levels (Warncke, 1996). Elevated root nitrate concentration in carrot roots is problematic for processors, as excessive nitrates pose health risks such as infantile methaemoglobinaemia (Santamaria, 2006). As a result, government regulation of nitrate levels, particularly in Europe, increasingly dictate maximum tolerance levels. For example, in Poland, the maximum allowable nitrate level in carrot roots is 200 ppm on a fresh weight basis (Gajewski et al. 2009). Because of the competing interests between strong healthy petioles for harvest efficiency and maintaining low root nitrate concentrations, a delicate balance must be struck with N management late in the season.

Objectives and hypotheses. Unfortunately, growers currently have only limited information on the optimal source, rate and timing of late N applications to help them negotiate these tradeoffs. This study aimed to help fill this knowledge gap, by addressing two main objectives: 1) To evaluate the effect of late-season N material and delivery method on petiole strength and carrot root nitrate concentration, and 2) To characterize the effects of N rate on petiole strength and carrot root nitrate concentration. For objective 1 we hypothesized that “Environmentally Smart Nitrogen” (ESN[®]) (42N-0P-0K) (Nutrien [formerly Agrium] Saskatoon, SK, Canada) a polymer-coated urea (PCU) and foliar applied urea ammonium nitrate (UAN) (28N-0P-0K) will maintain stronger petioles while maintaining lower CRN concentration than the current grower standard program which uses urea (46N-0P-0K) treated with the urease inhibitor Agrotain[®] (U+UI) (Koch Agronomic Services, Wichita, KS, USA). For objective 2 we hypothesized that petiole strength and CRN concentration would be greatest at higher late-season U+UI rates.

Materials and Methods

Plot establishment. A field trial was conducted in 2015 to evaluate the effects of late season N application on carrot petiole strength and carrot root nitrate concentration. A grower-cooperator field site was selected in August 2015 where processing carrots had been established in early May. The trial was located at 43°44'19.18" N, 86°14'18.68" W on Covert Sand typical organic matter content of this soil type is 0.85% and typical CEC is 2.0 meq/100g (NRCS, 2018). Field preparation was accomplished using a custom built strip tiller consisting of a shank followed by a liquid fertilizer tube, berm forming disks, and 23 cm wide hydraulically driven rotary cultivator. During strip tillage 15.69 kg/ha N from urea ammonium nitrate (UAN) was injected behind the shank to a depth of approximately 15 cm below the carrot row across all plots. N applications totaling 94.15 kg N/ha were made prior to plot establishment by the grower collaborator in top-dress applications of U+UI, with the final application of 33.63 kg N/ha occurring on 12 August, 2015. Management of insects, diseases and weeds was conducted by our grower collaborator, in accordance with standard grower practices (Bird et al., 2015; Zandstra, 2013).

Experimental treatments and schedule. Experimental plots were established on 20 August, 2015, and included two studies (Table 3.1). The first, focused on the effects of N delivery system at a given rate of total late N application (25.2 kg N/ha). Three systems were evaluated: 1) a single application of PCU (Late PCU); 2) a single application of U+UI (Late U+UI); and 3) four split applications of foliar applied UAN (Late Foliar) (Table 3.1). For each application timing in the Late Foliar system, treatments were applied at 6.3 kg N/ha with water as the carrier and a spray volume of 175 L/ha. The second study evaluated the impact of four late-season rates of U+UI: 0, 25.2, 50.4, and 75.7 kg N/ha (Table 3.1). The treatments were arranged in a randomized complete block design with four replications. Plots measured 3.2 m by 12.2m each having two beds of three rows of carrots with rows spaced 46 cm apart. For a schedule of major field operations, see Table 3.2.

Data collection. Carrots were harvested on 15 Oct. 2015 to assess treatment effects on total carrot yield. In each plot, carrots from 6.1 m of row were counted and weighed for yield. In addition, a subsample of 10 carrots from each plot was used to evaluate shoot dry weight, carrot petiole strength and

Table 3.1: Treatment list for application system and late-season U+UI studies, 2015.

	Application Date(s)
Application system^z	
Late-season PCU	20 Aug.
Late-season U+UI	9 Sept.
Late-season Foliar ^y	9, 17, 24, 30 Sept.
Late-season UA rate study^x	
0	N/A
22.4	9 Sept.
44.8	9 Sept.
67.3	9 Sept.

^zrate in each system was 25.2 kg N/ha; Poly-coated urea (PCU); Urea + Agrotain (U+UI).

^y6.3 kg/ha UAN (28N-0P-0K) applied on each date.

^xRate of U+UI in kg N/ha.

Table 3.2: Schedule of main field operations and data collection events, 2015.

Event	Date
Late-season PCU treatment established ^z	20 Aug.
Late-season U+UI rate study established	9 Sept.
Late-season foliar application 1	9 Sept.
Late-season foliar application 2	17 Sept.
Late-season foliar application 3	24 Sept.
Late-season foliar application 4	30 Sept.
Carrots harvested for yield and final stand	15 Oct.
Petiole strength sample	15 Oct.

^zNitrogen managed by grower with 94.15 kg N/ha applied prior to this date.

Carrot petiole strength was measured on each of the ten plants per plot with a Shimpo FGV-100XY force gauge (Shimpo, Wilmington, NC, USA) to determine the amount of force required to separate the petioles from the crown of the plant. Individual carrot roots were held stationary in a vice. The force gauge was then clamped to petioles just above the root crown and an even force was applied until the petioles broke. The peak force required to break the petioles was recorded. Carrot shoot biomass was measured on the shoots of the ten carrot plants used for petiole strength testing. The shoot tissue was dried at 60° C until a stable dry weight was reached.

Carrot root nitrate was determined by taking a 2.5 cm segment from the middle of the carrot roots from the petiole strength subsample. The sections were then diced, dried at 60° C and ground to pass through a 1 mm mesh. The ground carrot root tissue was extracted with 1 M potassium chloride in water following a method adapted from Binford et al. (1990). The extracts were tested for nitrate concentration by cadmium reduction on a Lachatt Quickchem flow-through colorimetric analyzer (Hach Company, Loveland, CO, USA) at the Michigan State University Soil and Plant Nutrient Laboratory. Dry weight basis CRN data were converted to fresh weight basis by dividing the dry weight CRN concentration by the ratio of fresh to dry carrot root weight.

Statistical analysis. Analysis of the effects of N system on yield, final carrot stand, carrot shoot biomass, petiole strength, and carrot root nitrate concentration were conducted in SAS (SAS Institute, 2012) using PROC MIXED procedures, with system treated as a fixed effect, and replicate as a random effect. Rate effects on the same responses were analyzed separately with rate as a fixed effect and replicate as a random effect. Normality assumptions were tested on residuals in SAS using the UNIVARIATE procedure Shapiro-Wilk ($P \leq 0.05$). CRN data were natural log transformed to improve normality. Transformations were not needed on any other responses. Where significant system or rate effects were found, means were separated using fishers protected LSD at the $P \leq 0.05$ level of significance.

Results and Discussion

System effects of late-season N. No late-season N application system effects were detected on any of the measured parameters with the exception of CRN (Table 3.3). CRN concentrations were greater in the Late PCU system compared to the Late Foliar system, although this effect was only marginally significant ($P=0.0670$ and $P=0.0617$, for CRN concentration on dry or fresh weight basis, respectively).

The lack of N system effects on carrot yield and carrot stand is not surprising, given that approximately 94 kg N/ha had been applied by the grower prior to initiation of the experiment, resulting in a seasonal total N rate of approximately 120 kg N/ha for all treatments in the system study. The marginal effect of system on CRN, where PCU had a higher concentration of CRN compared to the foliar application, provides weak support for the idea that split foliar applications of N may reduce the risk of nitrate accumulation in the root. However, it is likely that foliar applications resulted in less efficient uptake of applied N and greater losses of N to the environment. In general N uptake by foliage is relatively inefficient compared to root uptake. For example, in raspberry only 50% of N applied to leaves is absorbed by leaves (Reikenberg and Pritts, 1996). Alternatively, foliar applications may have resulted in a different distribution of N in root vs shoot tissue. Unfortunately, we did not assess shoot N accumulation in this study, so cannot determine which of these possibilities is more likely. In any case, the levels of CRN observed in all treatments was well below health thresholds, so the small differences in nitrate accumulation observed in response to system have little practical significance for growers.

Rate effects of late-season N. Results of our analysis showed a marginally significant ($P=0.07$) effect of late-season applied U+UI on carrot yield (Table 3.4); in particular, late season U+UI applications at 75.7 kg N/ha resulted in 13% higher yield compared to the treatment receiving no late season N. In contrast, Warncke (1996) did not detect any yield effect resulting from late season applications of N. Such variation in yield response to late N applications is not surprising, given differences in early N application rates, soil type, and weather conditions across years and sites. Our results suggest that substantial economic benefits may be attained by late N applications in some years, and that further research is needed to understand conditions under which such yield improvements may be expected.

Carrot shoot biomass was influenced by late season N rate (Table 3.4). In particular, we found that carrot shoot biomass (on a per ha basis) was greater in all treatments receiving late season N

Table 3.3: Late-season N application system effects on: carrot yield, carrot density, shoot biomass, petiole strength, and carrot root nitrate.

	Yield		Density		Shoot Biomass	
System effect^z	---Mg/ha---		-1000/ha-		---Mg/ha---	---g/Plant---
PCU	96.0	(3.6)	356	(14)	1.59	(0.1) 10 (0.68)
U+UI	98.6	(4.8)	363	(20)	1.57	(0.1) 9.74 (0.52)
Foliar	99.6	(5.1)	346	(19)	1.44	(0.1) 9.38 (0.67)
ANOVA	-----Significance (P-value)-----					
System	0.8206		0.8032		0.4094	0.768

^zLate-season nitrogen rate was 25.2 kg N/ha across all systems.

^yAlthough analysis was conducted on natural log transformed data, means and standard errors of non-transformed data are provided for ease of interpretation

Table 3.3: (Cont'd).

	Petiole Strength	Carrot Root Nitrate ^y	
System effect^z	---Newton---	-Dry ppm NO ₃ ⁻ -	-Fresh ppm NO ₃ ⁻ -
PCU	180 (25)	71.7 (12.7)	7.0 (1.1)
U+UI	174 (21)	55.8 (3.9)	5.4 (0.2)
Foliar	188 (9)	49.0 (3.9)	4.9 (0.5)
ANOVA	-----Significance (P-value)-----		
System	0.8739	0.0670	0.0617

^zLate-season nitrogen rate was 25.2 kg N/ha across all systems.

^yAlthough analysis was conducted on natural log transformed data, means and standard errors of non-transformed data are provided for ease of interpretation.

Table 3.4: Late-season urea rate effects on: carrot yield, carrot density, shoot biomass, petiole strength, and root nitrate.

	Yield		Density		Shoot Biomass				
Rate effect^z	-Mg/ha-		-1000s/ha-		-----Mg/ha-----		-----g/Plant-----		
0	89.6	(2.5)	338	(18)	1.18	(0.12)	B ^y	7.9	(0.9) B
25.2	98.6	(4.8)	363	(20)	1.57	(0.09)	A	9.7	(0.5) AB
50.4	97.1	(1.6)	343	(10)	1.62	(0.06)	A	10.6	(0.7) A
75.7	101.1	(3.2)	387	(12)	1.49	(0.11)	A	8.6	(0.4) B
ANOVA	-----Significance (P-value)-----								
Rate	0.0746		0.1563		0.0408		0.0433		

^zNitrogen rate kg N/ha from U+UI (46N-0P-0K).

^yMeans not connected by the same letter within the same group in a column are significantly different $\alpha = 0.05$.

^xAlthough analysis was conducted on natural log transformed data, means and standard errors of non-transformed data are provided for ease of interpretation.

Table 3.4: (Cont'd).

	Petiole Strength	Carrot Root Nitrate ^x			
Rate effect^z	-Newton-	---Dry ppm NO ₃ ⁻ ---		-Fresh ppm NO ₃ ⁻ -	
0	198 (26)	51.6 (6.0)	B	5.2 (0.9)	C
25.2	174 (21)	55.8 (3.9)	B	5.4 (0.2)	BC
50.4	213 (36)	177 (92.6)	AB	17.6 (9.6)	B
75.7	152 (26)	332 (44.6)	A	32.3 (4.7)	A
ANOVA	-----Significance (P-value)-----				
Rate	0.0802	0.0071		0.0024	

^zNitrogen rate kg N/ha from U+UI (46N-0P-0K).

^yMeans not connected by the same letter within the same group in a column are significantly different $\alpha = 0.05$.

^xAlthough analysis was conducted on natural log transformed data, means and standard errors of non-transformed data are provided for ease of interpretation.

compared to the 0 kg N/ha control treatment. However, on a per plant basis, we found that shoot biomass was only detectably different from the control at the 50.4 kg N/ha rate, perhaps due to high variability in this response. In general, our results are consistent with Makries and Warncke (2013), who found a strong relationship between late season N application and shoot biomass.

The rate effect of late-season applied U+UI was marginally significant for carrot petiole strength ($P=0.0802$), and did not follow a clear pattern with rate. The high level of variability in petiole strength measurements suggests that a greater sample size was necessary to achieve sufficient power to detect meaningful differences. Future studies evaluating the relationship between laboratory tests of petiole strength and harvest efficiency are necessary to better quantify the practical effects of late N management.

On both the fresh and dry basis, carrot root nitrate increased with late-season N rate (Table 3.4). In particular, root nitrate accumulation was approximately 7-fold greater at the 75.7 kg N/ha rate compared to the 0 kg N/ha control, and approximately triple the level at the 50.4 kg N/ha rate. This supports the findings of (Warncke, 1996) that elevated plant available N close to harvest can lead to higher concentrations of NO_3^- in carrot roots. However, while it is important to note that our extraction process was different than those used in other studies, the highest CRN levels observed in this experiment were well below established thresholds which are based on fresh carrot tissue (Santamaria, 2006).

Summary and Conclusion

Our results suggest that foliar application of UAN may help to reduce CRN. However, these effects were only marginally significant, and may have been the result of greater N losses to the environment rather than greater allocation of N to shoot tissue relative to root tissue. More research is needed to better understand the fate of late season foliar applied N in carrot. In particular, foliar application should be assessed at lower N rates, and the fate of N in those systems evaluated in more detail. In addition, it would be useful to assess how foliar UAN might interact with carrot leaf blight. Increasing N rate late in the season increased CRN as we had hypothesized, however the concentration we saw on a fresh weight basis were far below threshold for concern.

Under the conditions of this field study, we saw a surprising yield response to late-season N rate. A conservative estimated processing carrot value of \$75/Mg (USDA-NASS,2018), suggests that applying 75.7 kg N/ha in early September may have increased gross return by approximately \$860/ha. With urea prices of approximately \$0.18/kg N this would result in an estimated net return of approximately \$846/ha. While this shows a potential benefit of late-season N application, it is important to note that this yield increase was only marginally significant and based on data from one year.

These results suggest that N was more limiting than anticipated given grower application rates prior to initiation of the study. Better characterization of soil N concentrations during this study would have helped clarify the relevance of our results to other fields and years. Future studies, evaluating the effects of late N applications under diverse soil and climate conditions are needed to help formulate grower recommendations with greater confidence. In addition, evaluation of interactions between late N management and disease and insect pests would be helpful for helping growers optimize their fertility management practices.

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