Relationship Between Nitrogen Fertilization and Cercospora Leaf Spot and Alternaria Leaf Blight of Carrot

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Abstract. *Alternaria* leaf blight (ALB) and *Cercospora* leaf spot (CLS) are economically important diseases of carrot in Ontario. Field experiments were conducted in the Holland Marsh, Ontario, to determine the effect of nitrogen (N) application rates on both diseases. Five rates of N were applied to organic and mineral soils in which two carrot cultivars, Idaho and Fontana, were grown in each of 2002, 2003, and 2004. Both diseases were rated every 2 weeks on a scale of 0 (healthy) to 10 (tops destroyed), and the number of live (green) leaves per plant was assessed at harvest. In addition, three N rates were applied to carrot plants grown in the greenhouse, and the plants were inoculated with *Alternaria dauci* (Kühn) Groves and Skolko. Disease severity, senescence, and sap nitrate-N concentration were assessed. In the field trials, the response of ALB and CLS to N application rate was relatively consistent across cultivar, soil type, and year. Area-under-the-disease-progress curves typically increased with decreasing N rate for both diseases. In lower N treatments, this resulted in fewer live leaves per plant at harvest. In the greenhouse, ALB severity increased with increasing amount of leaf senescence at final assessment. The results suggest that N application rate could be used to reduce the need for fungicide applications to control these diseases in the field.

Alternaria leaf blight (ALB), caused by *Alternaria dauci* (Kühn) Groves and Skolko, and *Cercospora* leaf spot (CLS), caused by *Cercospora carotae* (Passerini) Solheim, are important diseases of carrot crops in Ontario. *Alternaria* leaf blight symptoms usually appear in early August and the percent of foliage affected increases until harvest. The disease predominates on older and senescing leaves (Rotem, 1994; Soteris, 1979). *Cercospora* leaf spot symptoms typically appear in early July and continue until harvest. The disease can occur anywhere on carrot foliage but is usually most severe on younger leaves (Kushalappa, 1994). Both diseases begin on leaflets and can spread to petioles. Severe epidemics of either disease can lead to leaf senescence and general weakening of the foliage. This can cause substantial reductions

in yield because the foliage may break off during mechanical harvest, leaving marketable carrots unharvested (Langenberg, 1975).

Research has established a relationship between fertilization practices and the severity of ALB alone or the ALB/CLS complex. The severity of ALB was decreased by increasing levels of fertilizer application (nitrogen, phosphorus, and potassium) in Israel (Vital et al., 1999) and Florida (White et al., 1983), possibly as a result of delayed leaf senescence at higher rates of fertilizer application and, as a result, delayed infection of the foliage by *A. dauci* (Vital et al., 1999). Studies examining the ALB/CLS complex showed that severity of the disease was reduced by increasing nitrogen (N) fertilizer application rate in Michigan (Warncke, 1996) and Ontario (Westerveld et al., 2002). However, the response of CLS to N fertilization is not as well defined as for ALB. *Cercospora* leaf spot severity in the greenhouse increased with increasing N concentration in the nutrient solution (Thomas, 1943), and in a field study, no relationship was found between CLS severity and leaf N concentration (Tremblay and Charbonneau, 1993). To our knowledge, no trials have yet been done to examine the effects of N application rate apart from phosphorus (P) and potassium (K) application on ALB and CLS individually in the field, but this research is necessary to adjust recommended N rates appropriately based on the effect of N rate on ALB and CLS severity.

There is a possibility that a reduction in recommended N rates may be legislated for

vegetable crops in Ontario based on the Nutrient Management Act and the Clean Water Act in the province (Government of Ontario, 2002, 2006). This probably will not have much direct effect on carrot yield because there is no yield response of carrot crops to N on organic soils in Ontario, and the response of carrot crops on mineral soil is minimal unless residual soil N concentrations at seeding are very low (Westerveld et al., 2006a). However, the potential interactions between N nutrition of a carrot crop and severity of ALB and CLS could complicate N management of the crop. To develop fertilization strategies that will minimize ALB and CLS severity while optimizing carrot yields, research is required to determine whether N fertilizer apart from P and K application has an effect on either disease. In addition, it is important to determine which of the two diseases is influenced by N nutrition of the crop, because the severity of one disease in relation to the other is dependent on weather and location. Furthermore, studies are required to determine the mechanism of interactions between N fertilization and ALB and CLS severity to identify fertilization practices that may help reduce disease severity. It would also be valuable to determine if the effects of N application rates on disease severity are consistent among carrot cultivars.

The objectives of this study were to identify: 1) the effects of N application rate apart from P and K application on ALB and CLS severity on two carrot cultivars with different levels of susceptibility to the two diseases on each of two soil types; 2) the relationship between ALB and CLS severity and nitrate-N (NO₃-N) concentration in carrot leaves; and 3) the nature of the relationship between leaf senescence and ALB severity.

Materials and Methods

Nitrogen rate field experiments. Field experiments were conducted on mineral and organic soils on the Holland/Bradford Marsh (long. 44°5' N, lat. 79°35' W), Ontario, Canada, near the University of Guelph Muck Crops Research Station from 2002 to 2004. The organic soil, a Hemic Histosol, contained 60% to 80% organic matter and had a pH of 6.1 to 6.8. The mineral soil, a Typic Haploluquoll, contained 1.0% to 3.5% organic matter and 90% sand and had a pH of 7.9 to 8.4. Carrot cultivars with different levels of susceptibility to ALB and CLS, Idaho (semi-susceptible to both diseases) and Fontana (highly susceptible to both diseases), were used in all field experiments. Carrots were seeded using a Stanhay precision seeder (Stanhay Webb Ltd., Grantham, U.K.) into the organic soil on 24 May 2002, 2 June 2003, and 21 May 2004; and into the mineral soil on 3 June 2002, 2 June 2003, and 20 May 2004. Each N rate trial was arranged in a split block design with cultivar as the main factor and N rate as the subfactor with four replications of each treatment combination. Each experimental unit (split plot) in the organic soil site

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consisted of four beds, 5 m in length, 20 cm high, spaced 86 cm apart, and planted at a seeding rate of 80 seeds/m. Each experimental unit (split plot) in the mineral soil plot consisted of eight beds, 10 m in length, 20 cm high, spaced 86 cm apart, at a seeding rate of 80 seeds/m. Within each bed, carrots were seeded in three rows spaced 5 cm apart. Carrots were grown on the same two sites, and the same randomization of treatments was used for the duration of the study in an attempt to reduce residual N levels over time in low-N treatments. The mineral soil beds were reformed twice during the season in all 3 years.

Nitrogen was applied as ammonium nitrate at 0, 50%, 100%, 150%, and 200% of the recommended rates on organic (60 kg-ha⁻¹ N applied preplant) and mineral soil (110 kg-ha⁻¹ N split as 66% applied preplant and 33% applied as a sidedress when the plants were 10 cm tall) (Ontario Ministry of Agriculture and Food, 2002). Nitrogen recommendations were not based on soil tests because soil test-based recommendations are not currently offered for carrot crops in Ontario. Spring 2002 N concentrations in the top 30 cm of soil before the start of the experiment, measured using one sample per block, were 24.4 mg·kg⁻¹ NH₄⁺, 89.1 mg·kg⁻¹ NO₃⁻, and 2.4% total N for the organic soil trial site; and 2.4 mg·kg⁻¹ NH₄⁺, 2.3 mg·kg⁻¹ NO₃⁻, and 0.09% total N for the mineral soil trial site. Soil samples were collected and nutrient analyses were completed throughout the experiment, but for another study (Westerveld et al., 2006b).

At the first appearance of leaf blight symptoms, the entire canopy in a 2.5-m-long section of the two middle rows of each experimental unit was assessed every 2 weeks using a visual rating scale of 0 to 10 (0 = no symptoms, 1 = less than 10 lesions on the leaves, 2 = 10 to 19 lesions mainly on leaves, 3 = 20 to 29 lesions mainly on leaves, 4 = 30 to 39 lesions on leaves and less than 10 lesions on petioles, 5 = greater than 40 lesions on leaves and 10 to 19 lesions on petioles, 6 = greater than 40 lesions on leaves and 20 or greater lesions on petioles, 7 = 20% to 39% of leaves destroyed, 8 = 40% to 59% of leaves destroyed, 9 = 60% to 79% of leaves destroyed, and 10 = 80% to 100% of leaves destroyed) (adapted from Westerveld et al., 2002). Area-under-the-disease-progress curve (AUDPC) values were calculated for each treatment based on the following equation (Shaner and Finney, 1977):

$$\text{AUDPC} = \frac{[(\text{DSR}_{\text{Day2}} + \text{DSR}_{\text{Day1}}) \cdot D]/2 + [(\text{DSR}_{\text{Day3}} + \text{DSR}_{\text{Day2}}) \cdot D]/2}{2}$$

where DSR is disease severity rating and D is the number of days between rating dates

At harvest, the number of live (green) leaves on 10 carrots per plot was recorded. The harvest dates for the organic soil trial were 18 Oct. 2002, 27 and 28 Oct. 2003, and 21 Oct. 2004; and the harvest dates for the mineral soil trial were 24 Oct. 2002, 23 and 24 Oct. 2003, and 26 Oct. 2004. No fungi-

cides were applied for leaf blight control in 2002 on either soil type. As a result of higher disease pressure in 2003 and 2004, a fungicide program was used in those years. In 2003, Bravo (chlorothalonil 50%; Syngenta Crop Protection Canada Inc., Guelph, Ontario, Canada) was applied at a rate of 3.0 L·ha⁻¹ a.i. to the organic soil trial on 18 Aug. In 2004, Lance (boscalid 70%; BASF Canada, Guelph, Ontario, Canada) was sprayed at 315 g·ha⁻¹ a.i. on each of 6 and 23 Aug. on the organic soil trial and on each of 9 and 23 Aug. on the mineral soil trial.

Three times during the growing season (55 to 66 d after seeding, 87 to 96 d after seeding, and 116 to 126 d after seeding), 16 petioles from recently mature leaves were collected at random within the middle two rows of each plot for NO₃-N analysis. The petioles were separated into four groups of four petioles and sap was extracted from each group using a handheld garlic press. The sap was tested for NO₃-N content using a Horiba "Cardy" Model C-141 NO₃⁻ meter (Horiba Co., Kyoto, Japan). The mean sap NO₃-N concentration each year was compared with season-long AUDPC data for each cultivar, soil type, and year using linear correlation analysis.

Greenhouse experiments. Trials to determine the relationship among ALB severity, sap NO₃-N concentration, and leaf senescence were conducted in the greenhouse in the winter and spring of 2004. Carrot cvs. Idaho and Fontana were seeded into 15-cm pots filled with 99% pure silica sand at eight to 10 seeds per pot and thinned to three plants per pot after emergence. Pots were drip-irrigated daily throughout the trial. After emergence, a 50% Hoagland solution lacking N (Hoagland and Arnon, 1938) was prepared and pots were flooded with 500 mL of the solution twice per week. Nitrogen treatments were applied during each watering and consisted of three N rates added as ammonium nitrate at 50%, 100%, and 200% of the N required for a 50% Hoagland solution. There were four replications per N rate-by-cultivar combination, and each replication consisted of two pots, one for plants inoculated with *A. dauci* and one for plants treated with water. The trial was arranged in a randomized complete block design. Before inoculation, petioles from four youngest fully mature leaves were collected from plants of each N rate-by-cultivar combination and tested for NO₃-N content using a Horiba "Cardy" Model C-141 nitrate meter as described previously.

A field isolate of *A. dauci* collected from the University of Florida Mid-Florida Research and Education Center in Apopka, FL (courtesy of J. Strandberg) was selected for this study, because we were unsuccessful in isolating the fungus from field experiments as a result of repeated contamination with *A. alternata* and very low spore production by *A. dauci*. The isolate was subcultured several times on carrot leaf agar from which conidia were harvested for inoculum (Strandberg, 1987). Plates were placed under fluorescent grow lights (30 W GE Bright Stik Gro and

Sho; General Electric Canada, Mississauga, Ontario, Canada; 470 lumens) with 18-h daylength and a temperature between 21 and 26 °C. When the carrots in the greenhouse were at the 10-leaf growth stage, the cultures of *A. dauci* were flooded with a 0.01% Tween 80 (v/v) solution (Carisse and Kushalappa, 1990) and conidia were dislodged into a suspension using a glass rod. The spore suspension was passed through a 100-mesh sieve and adjusted to 1 × 10⁴ spores/mL using a hemocytometer. A mature leaf from each pot was sprayed with the conidial suspension using a Badger-350 artist airbrush (Badger Airbrush Co., Franklin Park, IL) (Carisse and Kushalappa, 1990). To prevent inoculation of additional leaves on the plant, the other leaves of the plant were pulled away from the chosen leaf during inoculation. A single leaf was chosen rather than whole plants as a result of insufficient spore production from the *A. dauci* cultures and the resulting low volume of the appropriate concentration of the conidial suspension available. The conidial suspension was used immediately after preparation. The inoculated leaves were rated for senescence before inoculation using a scale of 0 to 10, where 0 = dark green leaf, 1 = moderately green leaf, 2 = light green leaf, 3 = mild chlorosis on a portion of the leaf, 4 = mild chlorosis on the whole leaf, 5 = moderate chlorosis, 6 = major chlorosis, 7 = mild necrosis on a portion of the leaf, 8 = mild necrosis of the whole leaf, 9 = moderate necrosis, and 10 = complete necrosis. Three water agar plates (10 cm diameter) were sprayed with the conidial suspension before, during, and after plant inoculation to determine the percent spore germination of the inoculum. The plates were then placed in the dark at room temperature (21 ± 2 °C) and assessed after 3 d for percentage of spores germinated. Half of the pots in the greenhouse were sprayed with 0.01% Tween 80 solution as a noninoculated control treatment. Individual leaves sprayed with the *A. dauci* conidial suspension or the Tween 80 solution were then covered with plastic bags for 2 d to maintain leaf wetness and promote infection. The inoculated leaves were tagged after the bags were removed. After 12 d, the number of ALB lesions on each inoculated leaf was counted.

The greenhouse trial was repeated as described previously, except the fertilizer was applied in the irrigation water at a rate equal to a 25% Hoagland solution lacking N, and pots were irrigated every 2 d (everyday without nutrients until seedling emergence) using ebb and flow benches. The nutrient solution was pumped into the bench to a 2.5-cm depth, which allowed for subirrigation of the pots. After 20 min, the nutrient solution was allowed to drain back into a holding tank. The nutrient solution was replaced every 2 weeks. The concentration of the nutrient solution was reduced from that of the first trial because of the more frequent fertigation used in the repeat trial. Nitrogen rates used were as described but based on the 25%

Hoagland solution. In this trial, entire plants were inoculated with the *A. dauci* conidial suspension. Leaf senescence was rated before inoculation using the 0 to 10 scale but assessed on the entire foliage per plant. The number of ALB lesions per leaf was counted 4 weeks after inoculation as a result of delayed symptom development in this trial.

Statistical analysis. The field data were analyzed using a split block variance analysis performed using Proc Mixed in SAS Version 8.0 (SAS Institute, Cary, NC). Data from all cultivars and years were combined for each disease and location for the analysis of variance. The sources of variation in the analysis of variance were: year (random), block (random), cultivar (fixed), cultivar*year (random), cultivar*block (random), cultivar*block*year (random), N rate (fixed), N rate*year (random), N rate*block (random), N rate*block*year (random), N rate*cultivar (fixed), N rate*cultivar*block (random), N rate*cultivar*year (random), and N rate*cultivar*block*year (random) (Federer and King, 2007). The greenhouse data were analyzed using analysis of variance based on a randomized complete block design, and the two greenhouse trials were not combined because of the differences in procedures between the two trials. Data were assessed for normality using the Shapiro-Wilk test of residuals in Proc Univariate in SAS version 8.0. Linear and quadratic regression analyses were performed using Proc GLM in SAS version 8.0. Data from the two cultivars were pooled if no significant N rate-by-cultivar interactions were identified. Linear correlation analyses were performed using Proc CORR of SAS version 8.0 for comparison between leaf NO₃-N concentration and ALB and CLS AUDPC in the field, leaf NO₃-N concentration, and ALB and CLS lesions per leaf in the greenhouse, and leaf senescence rating and ALB and CLS lesions per leaf in the greenhouse. A Type I error rate of 0.05 was selected for all statistical tests.

Results

Nitrogen rate field experiments. The severity of ALB and CLS, as indicated by AUDPC values, generally decreased with increasing N rate on both the mineral and organic soils. The exception occurred in 2002 on mineral soil in which no relationship between N rate and AUDPC was observed for both ALB and CLS (Table 1), which is probably the result of lower ALB and CLS severity in this trial compared with the other years and site. Data could not be combined among years as a result of N rate-by-year and cultivar-by-year interactions. However, there were no cultivar-by-N rate interactions except for CLS on organic soil in 2004, and consequently, results for cultivars were combined. On the mineral soil in 2002, low rainfall (58 mm in August and September compared with 191 mm in 2003 and 128 mm in 2004) and an inability to irrigate the plots resulted in some wilted areas resulting from moisture deficit, an increase in leaf blight

Table 1. Effect of nitrogen (N) application rate on severity of *Alternaria* leaf blight and *Cercospora* leaf spot as measured by area-under-the-disease-progress curve (AUDPC) for two carrot cultivars grown on mineral and organic soil sites in Ontario, Canada, from 2002 to 2004.

Soil type and N application rate ^z		Alternaria leaf blight AUDPC ^y			Cercospora leaf spot AUDPC ^y		
Percent of recommended N	N applied (kg·ha ⁻¹)	2002	2003	2004	2002	2003	2004
Organic soil							
0	0	333	389	432	428	410	399 ^y
50	30	310	378	397	416	410	368
100	60	278	348	375	384	398	367
150	90	279	336	354	382	373	345
200	120	280	336	360	375	374	312
Significance	L	***	***	***	***	**	***
	Q	*	NS	*	NS	NS	NS
	R ²	0.41	0.54	0.69	0.63	0.46	0.62
Mineral soil							
0	0	212	378	417	187	385	369
50	55	221	370	403	203	374	375
100	110	212	334	358	192	335	316
150	165	183	332	339	172	307	323
200	220	188	306	331	189	298	276
Significance	L	NS	***	***	NS	***	**
	Q	NS	NS	NS	NS	NS	NS
	R ²	—	0.57	0.50	—	0.66	0.34

^zTreatments on organic soil were applied entirely preplant, treatments on mineral soil were applied 66% preplant, 33% sidedress according to Ontario recommendations (Ontario Ministry of Agriculture and Food, 2002). Nitrogen was applied each year. Trials were arranged in a split block design with four replications.

^yBased on a biweekly rating using a scale of 0 to 10: 0 = no symptoms; 10 = 80% to 100% of leaves destroyed. Data from two cultivars, Idaho and Fontana, were combined, except *Cercospora* leaf spot data in the trial on organic soil in 2004 as a result of a significant N rate-by-cultivar interaction: cultivar Idaho data reported only; cultivar Fontana: L = ***, Q = NS, R² = 0.47.

NS, ***, ***Nonsignificant or significant at *P* = 0.05, 0.01, and 0.001, respectively. L = linear; Q = quadratic; R² = coefficient of determination.

severity within those areas, and increased variability in AUDPC values within the trials. Leaf blight was consistently more severe on 'Fontana' than 'Idaho' (e.g., AUDPC of 435 versus 331 for ALB and 461 versus 358 for CLS on the organic soil in 2004), but the response of ALB and CLS to N rate was consistent for both cultivars.

Increasing the rate of N applied also resulted in an increase in the number of live leaves per plant observed at harvest (Table 2) with the exception of the trial on mineral soil in 2002, which had low disease severity, and the trial on organic soil in 2004 (Table 2). Leaf blight was severe on the organic soil in 2004 throughout the season, even after three fungicide applications. *Cercospora* leaf spot symptoms developed on cotyledons in early spring, having spread from volunteer carrots infected with *C. carotae* within the trial. On mineral soil in both 2003 and 2004, there were twice as many live leaves per plant at harvest at the highest N rate compared with the lowest N rate (Table 2).

'Idaho' carrots had more live leaves per plant at harvest than 'Fontana' carrots on organic soil in all 3 years (e.g., 5.8 versus 4.7 in 2004) and on mineral soil in 2002 (data not shown). There were no differences between the cultivars in the number of live leaves per plant on carrots grown on mineral soil in 2003 or 2004 (data not shown). No N rate-by-cultivar interactions were identified for the number of live (green) leaves per plant at harvest, indicating that both cultivars had a similar response to the rates of N fertilizer. Thus, data from the two cultivars were

pooled. 'Fontana' carrots had a smaller canopy and produced fewer new leaves late in the season than 'Idaho' carrots based on observations and the live leaf per plant data at harvest.

Mean sap NO₃-N concentrations over the season were negatively correlated with AUDPC values for both ALB and CLS across both cultivars and both soil types in 13 of 16 cases in 2003 and 2004, but only for CLS on 'Fontana' carrots grown on organic soil in 2002 (Table 3). In most cases, especially early in the season, 'Fontana' carrots had higher sap NO₃-N concentrations than 'Idaho' carrots (e.g., 1748 versus 976 mg·kg⁻¹ at the early sampling date on the organic soil in 2004).

Greenhouse experiments. In the greenhouse trials with controlled rates of N applied to the potting medium, there was no effect of N rate on sap NO₃-N concentrations before *A. dauci* inoculation or on number of ALB lesions per leaf in the first trial (Table 4). However, NO₃-N concentrations increased and ALB lesions per leaf decreased with increasing N application rate in the second trial (Table 4). Leaf senescence decreased with increasing N rate in both trials (Table 4). There were no differences between the two carrot cultivars in ALB lesions per leaf, sap NO₃-N concentration, or senescence rating (data not shown), and both cultivars showed similar responses to N rate. Because there was no significant N rate-by-cultivar interactions, data from the two cultivars were combined for analysis and presentation. There was a positive correlation between the number of

Table 2. Effect of nitrogen (N) application rate on the number of live leaves per plant at harvest for each of two carrot cultivars each grown on mineral and organic soil sites in Ontario, Canada, from 2002 to 2004.

Soil type and N application rate ^z		Number of live leaves per plant ^y		
Percent of recommended N	N applied (kg·ha ⁻¹)	2002	2003	2004
Organic soil				
0	0	3.2	3.9	5.4
50	30	4.0	4.4	5.2
100	60	3.7	5.0	4.9
150	90	4.1	5.1	5.8
200	120	3.9	5.1	4.8
Significance	L	**	**	NS
	R ²	0.23	0.42	—
Mineral soil				
0	0	2.7	2.0	3.0
50	55	2.4	2.5	3.5
100	110	3.0	3.2	4.5
150	165	3.9	3.5	5.3
200	220	3.0	4.0	6.1
Significance	L	NS	***	***
	R ²	—	0.70	0.66

^zTreatments on organic soil were applied entirely preplant, treatments on mineral soil were applied 66% preplant, 33% sidedress according to Ontario recommendations (Ontario Ministry of Agriculture and Food, 2002). Nitrogen was applied each year. Trials were arranged in a split block design with four replications.

^yBased on a count of the number of green leaves on 10 plants. Data from two cultivars, Idaho and Fontana, were combined.

^{ns,*,***}Nonsignificant or significant at $P = 0.05$, 0.01 , and 0.001 , respectively. L = linear; R² = coefficient of determination.

Table 3. Linear correlation coefficients (r) for the comparison of mean foliar nitrate-N sap concentration and leaf blight severity caused by *Alternaria dauci* and *Cercospora carotae* as measured by area-under-the-disease-progress curve (AUDPC) for two cultivars of carrot, Idaho and Fontana, grown on each of an organic and a mineral soil in Ontario, Canada, from 2002 to 2004.

Soil type/yr	Alternaria leaf blight ^z		Cercospora leaf spot ^z	
	Idaho	Fontana	Idaho	Fontana
Organic				
2002	-0.25	-0.19	-0.27	-0.54*
2003	-0.49*	-0.51*	-0.47*	-0.27
2004	-0.49*	-0.50*	-0.66*	-0.54*
Mineral				
2002	-0.28	-0.27	-0.30	-0.43
2003	-0.64*	-0.31	-0.52*	-0.41
2004	-0.52*	-0.52*	-0.45*	-0.49*

^zBased on biweekly ratings on a scale of 0 = no symptoms to 10 = 80% to 100% of leaves destroyed. Trials were arranged in a split block design with four replications and five N application rates.

*Significant at $P < 0.05$ based on linear correlation analysis.

Table 4. Effect of nitrogen (N) application rate on number *Alternaria* leaf blight (ALB) lesions per leaf, nitrate-N (NO₃-N) concentration of leaves before inoculation, and senescence rating before inoculation of individual carrot leaves (Trial 1) or whole plants (Trial 2) with *Alternaria dauci* in greenhouse trials.

N rate ^z	ALB (lesions per leaf)		NO ₃ -N concn (mg·kg ⁻¹)		Senescence rating (0 = dark green, 10 = dead)	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
50	3.2	1.1	143	149	3.3	8.1
100	5.4	0.4	164	396	2.5	6.4
200	3.1	0.3	157	510	1.9	3.3
Significance	L	NS	NS	***	*	***
	R ²	—	—	0.86	0.44	0.90

^zPercent of the N required for a 50% Hoagland solution (Trial 1) or a 25% Hoagland solution (Trial 2).

^{ns,*,***}Nonsignificant or significant at $P = 0.05$, 0.01 , and 0.001 , respectively. L = linear; R² = coefficient of determination.

ALB lesions per leaf and leaf senescence ratings before inoculation of the plants in both greenhouse trials ($P = 0.0148$ and $r = 0.52$ for Trial 1, and $P = 0.0003$ and $r = 0.68$ for Trial 2). However, there was no correlation between ALB lesion number and sap

NO₃-N concentration in either trial. *Alternaria dauci* spores showed a 95% germination rate on the water agar plates that were sprayed with a conidial suspension on the date of carrot inoculation, and germination rate was not influenced by the timing of the

spray. *Alternaria* leaf blight symptoms did not develop on carrots sprayed with Tween 80 solution.

Discussion

Increasing the rate of N applied for carrot crops reduced the severity of both ALB and CLS in field trials on both organic and mineral soil and each of two cultivars, Fontana and Idaho, in most of the trials in this study. This supports previous reports of the impact of increased N rates on general carrot leaf blight severity by Warncke (1996) and Westerveld et al. (2002), but also shows that both pathogens are affected by the rate of N fertilizer used. Although the results were typically consistent among years, a significant N rate-by-year interaction occurred in all cases. This could potentially be the result of an increasing number of fungicide sprays per year as the trial progressed. No consistent trend in the response of disease severity to N application can be identified as a result of this increase in the number of fungicide sprays. *Cercospora* leaf spot severity typically decreased with increasing N rate on both mineral and organic soils in this study. This is the first study to show an effect of N fertilizer on CLS severity on carrots in the field. The results contrast those of an earlier greenhouse study conducted by Thomas (1943), which showed that increasing the N fertilizer rate increased the severity of the disease. A calculation of the rates used in that study suggests that all of the N rates were at or above sufficiency, and consequently, the increase in CLS severity at high N may have been an effect of excessive N application. The results of our study also differ from results of field studies conducted by Tremblay and Charbonneau (1993) on organic soils in Quebec, who found no correlation between leaf N concentration and CLS severity. However, the authors in that study only surveyed different carrot fields, and the effects of different N application rates were not examined.

For ALB, the results demonstrated that increasing the rate of N application decreased disease severity in the field. This is the first study to show a direct relationship between N fertility, apart from other nutrients, in the field and ALB. The susceptibility of carrot leaves to *A. dauci* increases as the leaves age (Soteros, 1979). Vintal et al. (1999) hypothesized that delayed leaf senescence in high fertility treatments causes a delay in ALB development and, as a result, less severe symptoms. In the current study, it was not possible to separate the effects of leaf senescence resulting from N deficiency alone in the field and the effects of leaf senescence on disease development, because ALB and CLS symptoms were found on all plants throughout the latter half of the growing season. In the greenhouse, ALB severity, as measured by the number of lesions per leaf, was higher on leaves that were more senescent. Because the senescence rating was done before inoculation of the leaves with *A. dauci*, the observed

differences in senescence and infection were associated with the N application rates and the effects of these treatments on plant physiology.

These data suggest that N was at least partially responsible for the effects observed by Vintal et al. (1999) and White et al. (1983) who studied the combined effects of N, P, and K on ALB severity. In contrast, Langston and Hudgins (2002) reported that increasing N rates did not decrease ALB severity. However, the N application rate in that study was only increased by 29%, which may not have been adequate to affect disease development as suggested by the results of the greenhouse trials in this study. An increase in disease severity with increasing leaf senescence has been demonstrated for other *Alternaria* diseases (Ali and Roy, 1981; Rotem, 1994).

In the plots receiving high rates of N in this study, constant replacement of older diseased leaves with newer leaves was observed on plants throughout the season. Plants grown with lower N rates produced fewer new leaves, especially late in the season. Disease ratings and the average number of lesions per leaf of both ALB and CLS would be lower in plots with high N rates even if there was the same total number of lesions per plant as in plots with lower rates of N as a result of an increase in production of young, disease-free foliage on plants growing in plots with high rates of N. A decrease in disease severity resulting from replacement of diseased leaves with new leaves has been demonstrated for other diseases such as take-all of wheat and powdery mildew of barley (Huber, 1980; Last, 1962). The main differences observed in disease severity between plants in high N versus low N plots were that plants given high N had fewer lesions on petioles and had fewer leaves with severe infections as reflected in the severity ratings and AUPDC values. Disease levels were higher in all of the seasons except mineral soil in 2002 than would occur with timely foliar application of fungicides.

Within each carrot cultivar evaluated in this study, severity of both ALB and CLS typically decreased with an increase in the mean season-long sap $\text{NO}_3\text{-N}$ concentrations. The exception was in the trials on both soil types in 2002, in which a correlation between sap $\text{NO}_3\text{-N}$ concentrations and disease severity only occurred for CLS on 'Fontana' carrots in organic soil. It is possible that the differences in $\text{NO}_3\text{-N}$ concentrations among N rates increased from year to year as a result of a cumulative effect, resulting in stronger correlations in the latter years of the experiment. 'Fontana' had consistently higher sap $\text{NO}_3\text{-N}$ concentrations and consistently higher disease severity than 'Idaho'. Within each cultivar, sap $\text{NO}_3\text{-N}$ concentration provided an indication of overall N status of the plant, which would have been directly related to leaf senescence and disease development. However, when comparing cultivars, $\text{NO}_3\text{-N}$ concentration might not give a good indication of overall N status of the plant because different cultivars may take up different

proportions of total N as NO_3^- or a different proportion of NO_3^- reduction may occur in the leaves as compared with the roots. Although 'Fontana' carrots always had higher sap $\text{NO}_3\text{-N}$ concentrations than 'Idaho', the former also had much weaker foliage and more senescent leaves than 'Idaho' carrots. Leaf production by 'Fontana' was improved through N application, especially on the mineral soil site in 2003 and 2004. This suggests that there was N deficiency in the plants although sap $\text{NO}_3\text{-N}$ concentrations were very high. Overall, it is possible that neither disease is influenced directly by sap $\text{NO}_3\text{-N}$ concentrations, because the cultivar with high levels of $\text{NO}_3\text{-N}$ had more foliar disease, but plants with higher levels of $\text{NO}_3\text{-N}$ had less disease.

The results of the field and greenhouse experiments in this study indicate that N fertilization can potentially be optimized to reduce the number of fungicide applications required to manage ALB and CLB in carrot crops on organic or mineral soils. This research showed an increase in the number of live leaves per plant at harvest in plots with high N rates, suggesting that mechanical harvest could be improved by these treatments. The exceptions were on mineral soil in 2002 resulting from low disease pressure and on organic soil in 2004. It is possible that the pathogen quickly overcame the beneficial effect of adequate N fertility at the higher rates of N applied in the 2004 trial on organic soil. Further research on the relationship between the N effects on leaf blight severity and the ability to mechanically harvest the crop is required to optimize the rate of N applications for this purpose. Overall, combining the use of fungicides and optimizing rates of N application could result in improved disease control and reduced environmental impact of excess N and fungicides. Given the linear response of CLS severity to N application rate, the N application rates that minimized disease severity were at least the maximum N rates tested of 120 kg ha^{-1} N on organic soil and 220 kg ha^{-1} N on mineral soil. The optimal rates of N application for minimizing ALB severity was between 96 kg ha^{-1} and the maximum rate tested of 120 kg ha^{-1} for organic soil plots and the maximum N rate tested of 220 kg ha^{-1} N for mineral soil. It was not possible to calculate optimal economic rates of N application for minimizing disease severity as a result of the linear response of disease severity to N application rate in most cases; the variable price of the carrot crop; and the unknown balance between fungicide and N application rates.

Development of ALB and CLS is influenced by N nutrition of a carrot plant. Higher rates of N fertilization typically reduced the severity of ALB and CLB in the field trials in this study. This resulted in an increased number of live leaves at harvest. Although ALB and CLS severity was affected by soil type, cultivar, and year, the response of ALB and CLS to N application rate was consistent between the two cultivars and the two soil

types over the 3-year study. The decrease in ALB severity was partially the result of delayed leaf senescence at higher N application rates. Higher rates of N reduced severity of both diseases by increasing production of new leaves compared with plants in plots with lower rates of N. Disease severity decreased with increasing leaf $\text{NO}_3\text{-N}$ concentration within each cultivar, but the susceptibility of the two cultivars to leaf blight was not directly related to $\text{NO}_3\text{-N}$ or total N concentration in the leaves. These results indicate that preplant soil N status may have a significant effect on ALB and CLS severity on carrot.

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