NITROGEN DYNAMICS OF THE CARROT CROP AND INFLUENCES ON YIELD AND ALTERNARIA AND CERCOSPORA LEAF BLIGHTS

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ABSTRACT

NITROGEN DYNAMICS OF THE CARROT CROP AND INFLUENCES ON YIELD AND ALTERNARIA AND CERCOSPORA LEAF BLIGHTS

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The influence of nitrogen (N) management (N rates: 0, 50, 100, 150, 200% of recommended; foliar N), cultivar ('Idaho' and 'Fontana'), soil type (organic and mineral), and year (2002, 2003, and 2004) on the seasonal patterns of N uptake, dry matter (DM) production, and DM and N partitioning were examined to understand carrot susceptibility to Alternaria (ALB) and Cercospora (CLB) leaf blights. Annual N application rate without rotation had minimal effect on carrot yield, quality, or storability, except in 2003 and 2004 on mineral soil when yield increased up to 200 and 91% of recommended N rates. Seedling death increased with increasing N rate in 2003 and 2004 on mineral soil. Increasing preplant N consistently decreased the severity of ALB and CLB on both soil types and for susceptible ('Fontana') and less susceptible cultivars ('Idaho'). Carrots developed fibrous roots up to 150 cm depth (50-65% below 30 cm) and N uptake per root was equal at each depth. Nitrogen and DM in the storage root accumulated slowly up to 50-60 days after seeding (DAS) and accumulated rapidly thereafter until harvest, whereas N and DM in the tops accumulated prior to 50-60 DAS and generally levelled off or declined beyond 100-120 DAS. Differences in ALB or CLB susceptibility among cultivars, treatments, or soil types were unrelated to leaf N concentration, DM or N

partitioning, or rooting depth and distribution. This work suggested that carrots can access deep soil N, and residual N from the preceding season had more effect on yield than current year application. The effects of high N rates on disease severity were partially explained by a delay in leaf senescence that delayed ALB development, and regeneration of leaves that increased tolerance to both diseases. Preplant N had more influence on yield and disease susceptibility than sidedressed or foliar applied N, a result attributed to deep N uptake and early season N partitioning to leaves. Carrots remove up to 280 $kg \cdot ha^{-1}$ N and can be used as an N catch crop to remove residual soil N. The results highlight the importance of integrating crop nutrition into disease management studies.

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AI	After inoculation
ALB	Alternaria leaf blight
CLB	Cercospora leaf blight
DAS	Days after seeding
DM	Dry matter
FNR	Fertilizer nitrogen recovery
GLM	General Linear Models
ICM	Integrated crop management
IPM	Integrated pest management
NH_4-N	Ammonium-nitrogen
NMA	Nutrient Management Act
NO_3-N	Nitrate-nitrogen
NS	Not significant
NUE	Nitrogen use efficiency
OM	Organic matter
P_c	Canopy photosynthesis

Chapter 1: Literature Review

1.1 Introduction

Understanding the complex relationships between a pest and its host requires an examination of many distinct fields of study including crop nutrition, pest management, crop physiology, and soil/plant relationships. Interdisciplinary research among these fields has become increasingly important in the past few decades because of the potential for pest suppression without a corresponding increase in environmentally damaging inputs. The complex relationship between insect and disease pests and crop nutrition is particularly important because host mineral nutrition interacts with all defence reactions and mineral nutrition is one of the main host plant processes affected by disease (Huber, 1980b). An understanding of this relationship can result in benefits for many sectors of the agri-food system in increased yield and quality, and improved compliance with increasingly strict environmental laws including the Nutrient Management Act (NMA) in Ontario.

In this chapter, research on the carrot (*Daucus carota* L.) crop, carrot N nutrition, N use efficiency (NUE), leaf blight, and the relationship between N and disease susceptibility will be discussed in order to identify gaps in current knowledge and to establish hypotheses that will be tested in the subsequent chapters.

1.2 Nitrogen Use Efficiency

Nitrogen use efficiency refers to the ability of a plant to convert N inputs into desired outputs (Lynch, 1998). Many definitions of NUE have been used for cropping systems, including: dry matter (DM) produced per unit N applied (Thorup-Kristensen,

2002), DM produced per unit N taken up by the plant (Berendse and Aerts, 1987), photosynthesis per unit N in the plant (Salisbury and Ross, 1992), and N from fertilizer removed in the harvested portion per unit N applied (Olson and Swallow, 1984). The most biologically meaningful definition is one that factors in the DM produced per unit N in the plant, and the length of time N remains active in the plant (Berendse and Aerts, 1987). This equates to DM produced per unit N taken up by the plant over the growing season (Berendse and Aerts, 1987). However, the most commonly used definition is DM produced in the harvested portion of the plant per unit N applied (Lynch, 1998), since the economic and environmental costs of fertilizer application are of primary importance to producers and to their compliance with environmental legislation. For this thesis, NUE will refer to DM produced in the storage portion of the carrot root per unit N applied, fertilizer N recovery (FNR) will refer to N fertilizer taken up in the harvested portion per unit N applied, and other definitions will be considered. Because of the many definitions used for NUE, no studies have examined actual NUE values as defined here, for the carrot crop.

1.3 Nitrogen and the Carrot Crop

1.3.1 The Carrot Crop

The carrot (*Daucus carota* L.) is a biennial plant that has been cultivated since around the tenth century (Rubatzky et al., 1999). Carrots are mainly grown for the fleshy pith and cortex tissues of the hypocotyl and taproot, which are composed predominately of parenchyma cells, and are produced in the first year of growth (Havis, 1939). Due to the high levels of carotenoids in the commonly grown orange cultivars, carrots are

considered an important component of a healthy diet (Rubatzky et al., 1999). Carrots provide 30% of the vitamin A available to consumers in the U.S. (Simon, 1992), and are considered a high value, small acreage crop (Rubatzky et al., 1999). In 2003, 1,031,700 ha of carrots were grown worldwide, which is 56% higher than a decade ago (F.A.O., 2004). In Canada, 9,500 ha were harvested in 2003, representing a farm gate value of $51,930,000, and making carrots the second most valuable field grown vegetable crop in the country (Statistics Canada, 2004).

1.3.2 Nitrogen and Carrots

Few studies have examined N metabolism, transport, or partitioning in carrots. Both the nitrate (NO_3^-) and the ammonium (NH_4^+) forms of N can be taken up by carrots (Goh and Ali, 1983), but the NO_3^- form predominates in agricultural soils. Nitrate reduction by NO_3^- reductase and nitrite reductase occurs primarily in the leaves in carrots, but the proportion of total plant NO_3^- reductase activity occurring in the roots increases with an increasing proportion of plant DM distributed to the roots (Darwinkel, 1975). For most temperate species, the proportion of NO_3^- reductase activity in the root also increases compared to the shoot as the N supply from the soil decreases (Andrews, 1986). The rate of NO_3^- reduction is highest in young leaves, and decreases in proportion to DM production as the plant ages due to reduced demand for proteins (Darwinkel, 1975). This decline in NO_3^- reduction also corresponds with a decrease in the rate of mineral absorption from the soil relative to production of photoassimilates over the growth period (Platenius, 1934). Further assimilation of N occurs via the glutamate synthase/glutamine synthetase pathway (Robinson et al., 1991). Root crops in general, including carrots, have

especially high concentrations of glutamine, predominately used as the storage from of N in the roots (Salisbury and Ross, 1992). The use of this N form for storage is presumably due to its low carbon (C):N ratio compared to most other amino acids (Salisbury and Ross, 1992). Glutamine concentration in roots increases as the N supply from the soil is increased from 22 to 162 $kg \cdot ha^{-1}$, a result likely due to storage of excess N (Kaack et al., 2001). Glutamine concentration in roots is also reduced under low N fertilization (Bazier et al., 1966). The predominant location of glutamine synthesis in carrots or its further metabolism have not been determined.

At the crop level, carrots apparently require little or no applied N when grown in temperate regions and some sub-tropical regions of the Northern Hemisphere such as Germany (Venter, 1979; Wiebe, 1987; Rühlmann and Geyer, 1993; Gutezeit, 1999), Finland (Evers, 1988), Scotland (Couper, 2001), France (Blanc et al., 1979), Oregon (Hemphill and Jackson, 1982), Florida (Burdine and Hall, 1976), Michigan (Warncke, 1996), Quebec (Hamilton and Bernier, 1975), Prince Edward Island (Sanderson and Ivany, 1997), and Ontario (Westerveld, 2002). Net mineralization rates of up to 150 $kg \cdot ha^{-1} \cdot yr^{-1}$ N in the top 60 cm of soil are reported for a sandy soil in Germany, providing, at least in part, some explanation for the lack of a yield effect (Gutezeit, 1999). Reported net mineralization rates are 46 $kg \cdot ha^{-1}$ N for a loam soil over the winter growing season in China (Chen et al., 2004), 77-146 $kg \cdot ha^{-1} \cdot yr^{-1}$ N for course loam soil in New Brunswick (Zebarth et al., 2004), <100->300 $kg \cdot ha^{-1} \cdot yr^{-1}$ N for various mineral soils in Ontario (Kay et al., 2004), and up to 1250 $kg \cdot ha^{-1} \cdot yr^{-1}$ N for organic soil in Florida (Reddy, 1982). Thus, it is possible that soil mineralization provides a large percentage of the carrot's requirements of N for yield.

There are several areas where a carrot yield response to N occurs. In predominately sandy soils in India, Indonesia, Japan, Texas, and Florida, carrot yields are increased by the application of up to 80, 150, 210, 112, and 280 $kg \cdot ha^{-1}$ N, respectively (Arora and Mathur, 1972; Burdine and Hall, 1976; Hipp, 1978; Hochmuth et al., 1999; Kumazawa, 2002). This response could be due to higher rainfall and increased leaching of N during the growing season (Hochmuth et al., 1999). In Texas, the yield response to N is only significant if the carrots are grown for longer than 128 days in sandy loam soil (Hipp, 1978). On newly cleared organic soil in Nova Scotia, carrots require up to 250 $kg \cdot ha^{-1}$ N, a result that can be attributed to rapid immobilization of N in soil organic matter (OM) (Bishop et al., 1973). In Japan, a reduction in N application rate from 256 $kg \cdot ha^{-1}$ N to 153 $kg \cdot ha^{-1}$ N in sandy soils lowers the NO_3-N concentration of groundwater from unacceptable to acceptable (<10 $mg \cdot L^{-1}$) in a predominately carrot growing region without affecting yields (Kumazawa, 2002).

Carrot quality is as important as yield in determining the marketability of the crop. There are no effects of N application rate on carrot quality as indicated by marketability and size in Florida (Burdine and Hall, 1976) or Ontario (Westerveld, 2002). Sugar concentration of carrot roots and root carotenoid concentrations increase with increased N application rate in some cases (Venter, 1979; Vereecke and Van Maercke, 1979; Hochmuth et al., 1999), but vitamin C concentration and carotene concentration are not affected by N application rate in other cases (Nilsson, 1979; Venter, 1979). Decreasing N fertilizer rates from 210 $kg \cdot ha^{-1}$ N to 170, 150 or 0 $kg \cdot ha^{-1}$ N in Japan improves carrot quality and income from carrot fields (Kumazawa, 2002). Application of 90 $kg \cdot ha^{-1}$ to carrots when the roots are 1 cm diameter in mid-July increases carrot

storage root splitting, but later sidedress applications do not affect root splitting (Bienz, 1965). Storability of carrot roots is unaffected by N application rate (Nilsson, 1979; Westerveld, 2002), but no studies have examined storability under deficient N conditions. Quality and storability must be studied under deficient N conditions to assess the potential risks of reducing N application rates.

The reason for the lack of yield response of carrots to applied N has not been fully investigated. However, there are many possible explanations for these observations. First, carrots have a deep and extensive root system. The carrot tap root reaches a maximum depth of 38.5 cm by 24 days after seeding (DAS) in Florida, which is deeper than the typical fertilized zone (White and Strandberg, 1978). In Denmark, carrots have a rooting depth of 1.6 m in sandy soil in mini-rhizotrons, and carrots reduce N concentrations in all layers of the soil profile up to 1.00 m depth by an average of 65% between early summer and harvest, resulting in a dramatic depletion in the N available in the 50-75 and 75-100 cm zones (Thorup-Kristensen and van den Boogaard, 1999). In addition, high soil N concentrations can restrict root growth and limit subsequent nutrient and water uptake (Klemm, 1966 in Thorup-Kristensen and van den Boogaard, 1999). Total length of fibrous roots on a single carrot plant ranges from 130 m in loose sandy soil to 300 m in compacted organic soil (Pietola and Smucker, 1998). Root hairs in carrots contribute little to increasing water or nutrient uptake efficiency because they are less than 0.04 mm in length (Pietola and Smucker, 1998). However, carrots have a root length to weight ratio of 250 to 350 $m \cdot g^{-1}$, which is higher than that of maize, sorghum, and soybean, and roots are often concentrated in the most fertile zone (Pietola and Smucker, 1998). An examination of the distribution of N uptake in the soil profile is required to identify

reasons for the lack of carrot yield response to applied N, and to adjust N monitoring practices to account for N available from deep in the soil profile.

It is also possible that carrots are more efficient at extracting N from the soil and partitioning it to the harvested portion of the plant, thus exhibiting high NUE. Many plants exhibit an increase in root:shoot ratio in deficient N conditions (Salisbury and Ross, 1992), a strategy that is likely to increase the extent of mineral absorption in the soil profile in proportion to shoot growth (Mardanov et al., 1998). Nitrogen is also transferred from the shoot to the root when N deficiency occurs (Burns, 1994). In root crops, the size of the storage root can also increase in relation to the shoot under N deficient conditions (Améziane et al., 1995; Villagarcia et al., 1998). The allocation of photoassimilates to the storage root throughout storage root development in root crops results in a corresponding increase in the fibrous root system due to increased availability of C and N compounds, and this is likely to cause improved nutrient and water uptake (Osaki et al., 1996). An additional factor that could be involved in the lack of yield response to applied N is that biennial plants are able to delay the filling of the storage root and focus on leaf growth early in the season when N is deficient (Heilmeier et al., 1994; Monson et al., 1994). At the end of the season, plants in low N conditions also mobilize much more photoassimilates from the leaves to the storage root than in high N conditions (Monson et al., 1994). In *Cirsium vulgare,* a biennial thistle with a storage tap root, plants given nutrient solutions containing 0.005, 0.025 and 0.125 $mol \cdot m^{-3}$ N have 15-22% lower relative energy costs of both producing and filling the storage root than plants given 0.625 or 3.125 $mol \cdot m^{-3}$ N (Monson et al., 1994). Relative costs are defined as the loss in canopy photosynthesis (P_c) that occurs by the storage of one unit of N or C

compounds. This is mainly due to lower relative growth rates in low N conditions, which means that there are lower relative costs for allocating N and C to storage root growth. Filling of storage tissue also occurs later under low N conditions when the costs of storage are reduced, because the alternative of increasing shoot growth at this time with the N and C compounds results in no additional DM production (Monson et al., 1994). The NUE of the carrot crop in terms of root growth, the distribution of N uptake, and the partitioning of N and DM to the storage root require further investigation in order to identify the N needs of the crop and provide explanations for differences in disease susceptibility.

Nitrogen partitioning of the carrot crop over the growing season has not been extensively examined, but there have been several studies on DM production and partitioning. Typically, the initiation of the storage root occurs between 13 and 34 DAS (Esau, 1940; Hole et al., 1987a; Hole and Dearman, 1991). This is followed by a period of exponential increase in both top and root dry weight anytime between 35 and 65 DAS (Hole et al., 1983). Beginning between 50 and 68 DAS there is a rapid linear increase in root dry weight until harvest (Platenius, 1934; Rubatzky et al., 1999; Reid and English, 2000; Strandberg, 2001). Beginning slightly earlier than the linear increase in storage root growth there is a rapid linear increase in top dry weight until 100 to 120 DAS followed by a plateau or slight decline thereafter (Platenius, 1934; Rubatzky et al., 1999). Storage root initiation and early development are not influenced by cultivar (Hole et al., 1983; Hole et al., 1987a), but it does affect the distribution of DM between the top and root (Hole et al., 1987b; Hole and Dearman, 1991). In Finland, carrot plants take up 150 $kg \cdot ha^{-1}$ N over the growing season, which accumulates slowly during the first 30 DAS

and then increases nearly linearly until harvest (Salo, 1999). There is no differentiation between the top and storage root in that study, and it is unknown whether N accumulation and partitioning follow similar patterns as DM production and partitioning. An assessment of the effects of N application rate or soil type on DM partitioning and the effects of N application rate, soil type, and cultivar on N partitioning in carrot is still needed in order to assess potential relationships between N and disease susceptibility and to identify key factors influencing NUE of the crop.

1.3.3 Nitrogen Monitoring

Despite the general lack of effect of N on yield in temperate regions, N monitoring of the crop, and in-field N monitoring in particular, has been studied because of the potential for improvement in N management of the crop in years when N deficiency exists. The use of a rapid NO_3^- test of petioles has facilitated assessment of the need for and timing of N top-dress application in carrot crops grown in Germany (Wiebe, 1987). Cardy meter NO_3-N tests are correlated with laboratory tissue NO_3-N results, as determined by KCl extraction and colourimetric analysis in Ontario (Westerveld et al., 2003a); however, a yield response is not evident in this study and critical NO_3-N concentrations cannot be established. A critical nutrient concentration is defined as the lowest concentration of a nutrient required for optimum growth and maturation (Macy, 1936). Furthermore, critical tissue NO_3-N concentrations determined in other regions are not useful for N management of carrots, onions, and cabbage in the province due to variations in climate, soil, and cultivar (Westerveld et al., 2003b). The Cardy NO_3-N meter can also be used for a rapid soil NO_3-N test, and this test is effective for

determining N requirements for cole crops in California (Hartz et al., 1993). Cardy NO_3-N readings are also highly correlated with laboratory soil NO_3-N results as determined by KCl extraction and colourimetric analysis in mineral and organic soils in Ontario (Westerveld et al., 2003a). Knowledge of critical NO_3-N concentrations is required under Ontario conditions for these tests to be effective tools for N management, and a yield response to N is required to establish these concentrations.

1.3.4 Carrots as Catch Crops

The main barrier to compliance with the NMA in Ontario is that certain crops, such as cole crops, require excessive amounts of N (up to 500 $kg \cdot ha^{-1}$) for maximum total and economic yield (Zebarth et al., 1991). In some areas of Ontario, production of these crops may be prohibited because of the potential for excessive losses of N (O.M.A.F., 2005). If the excess N from one crop can be utilized by another crop, avoiding N losses, there is potential for production of these crops with reduced environmental impact. Crops that are used for the purpose of removing excess nutrients from the soil are considered catch crops (Fream, 1905). Catch crops are traditionally considered crops grown during the off-season between the main crops in the rotation such as winter rye or oilseed radish (Vos et al., 1998). In a period from August to November in the Netherlands, catch crops, including winter rye, forage rape and oilseed radish, take up 10 to 180 $kg \cdot ha^{-1}$ N, 33% of which is recaptured after plow-down by the main crop in the following season (Vos and van der Putten, 1997; Vos and van der Putten, 2000). In Denmark, ten diverse catch crops all reduce the leaching risk substantially when grown after a Brussels sprouts crop (Thorup-Kristensen, 1994). There is a strong linear correlation between the amount of N taken up by a catch crop and the reduction in leaching of N during the same period (Vos

and van der Putten, 2004). In the Netherlands, catch crops reduce the N concentration of ground water below a vegetable field from well above the EU standard of 10 $mg \cdot L^{-1}$ to at or below the standard, and allow crop production to continue (Vos and van der Putten, 2004).

Several Ontario studies suggest that rotation crops can be as useful as winter cover crops in reducing NO_3^- leaching, although no studies have directly examined the potential for the use of a rotation cash crop as a catch crop. In contrast to Europe, where most of the catch crop studies have been conducted, Ontario soils are frozen for up to four months of the year, thereby reducing leaching losses during this period (Ryan et al., 2000). Soluble N accumulates in the soil over the winter in Ontario, due to death of N-rich micro-organisms, but this soluble N is lost primarily as gaseous N_2O during the spring thaw (Ryan et al., 2000). A study of corn, barley, and alfalfa rotations in Ontario revealed that 70% of the NO_3^- losses to ground water in fertilized plots occur during the period from November to April (Tan et al., 2002). However, when soil moisture over the growing season is adequate, as it is in irrigated vegetable crops, most of the NO_3^- in the soil is taken up by the crop, leaving much less to be leached during the winter (Tan et al., 2002). In addition, the greatest loss of NO_3^- due to leaching occurs when soils do not freeze (Tan et al., 2002). A study of continuous corn and a corn/wheat/soybean rotation reveals that the choice of a rotation crop is very important in determining total N losses due to leaching (Yiridoe et al., 1997). The addition of winter wheat into the rotation dramatically reduces NO_3^- leaching over the entire rotation. An examination of NO_3^- leaching over time in continuous corn in Ontario suggests that NO_3^- does not leach from the entire soil profile over the winter months, and there is a substantial accumulation of

NO_3^- at 90 cm depth by the spring (Sheppard and Bates, 1986). Finally, it is the long-term fertility of the soil that determines the NO_3^- levels available for leaching in a certain season, rather than fertilizer N applied during that season (MacDonald et al., 1989).

Together, these studies suggest that the use of a rotation cash crop with high NUE and deep rooting could reduce total N losses substantially by reducing N added to the entire rotation and removing N from lower levels of the soil profile. For example, NUE can be improved in the crop rotation by rotating deep rooted and shallow rooted crops in the proper sequence (Thorup-Kristensen, 2002). Carrots appear to require minimal applied N for optimum yield, can be grown during the full length of the growing season to capture as much N as possible, and can take up a large amount of N during the growing season (Westerveld, 2002). In addition, the deep rooting character of carrots allows for improved capture of N from deep in the soil profile where N from the previous year is likely to accumulate by the beginning of the growing season (Thorup-Kristensen, 2002). Consequently, it has been suggested that carrots could make a good catch crop under Ontario growing conditions (Westerveld, 2002).

1.4 The Nitrogen/ Leaf Blight Connection

1.4.1 Alternaria Leaf Blight

Alternaria leaf blight (ALB) of carrots is caused by the fungal pathogen *Alternaria dauci* (Kühn) Groves & Skolko. *Alternaria dauci* is a member of the *Fungi Imperfecti* (Class *Deuteromycetes*). Members of the *Alternaria* genus lack a sexual phase and reproduce asexually through the production of conidia. New genotypes can occur through horizontal gene transfer, mutations, and parasexualism (Rotem, 1994; Johnson et

al., 2000), which can allow for rapid adaptation to new conditions. Due to the lack of a sexual phase, it is difficult to classify imperfect fungi, and it has been suggested that *A. dauci* could be a forma specialis of *A. porri* (Ell.) Cif. along with *A. solani* Sorauer, the causal agent of early blight of tomato and potato (Neergaard, 1945; Kusaba and Tsuge, 1995).

Alternaria dauci is a weakly pathogenic organism that causes blight symptoms on carrots and many close relatives. Alternaria leaf blight is the most common and one of the most destructive diseases of carrots worldwide (Pryor and Strandberg, 2001; Pryor et al., 2002). It was first discovered in 1855 in Germany (Pryor and Strandberg, 2001). The pathogen overwinters on crop debris, seeds, or wild carrot relatives. Conidia are spread by wind, water, farm machinery, or field workers and land on carrot leaves. The conidia germinate and directly penetrate the leaf. Lesions develop in response to local cell death and plant defences. The lesions of ALB are irregular in shape, usually occur on the leaf margins, and are surrounded by a yellow halo (Figure 1.1). Symptoms of ALB usually occur on older and senescing leaves and begin during the mid- to late- growth phase, which occurs around the beginning of August in Ontario, but some seedling damping-off has also been attributed to *A. dauci* (Neergaard, 1945). Lesions can also develop on the petioles under severe conditions (Hooker, 1944), which can lead to accelerated leaf senescence. Susceptibility of carrot leaves to *A. dauci* infection is increased as the leaf ages (Soteros, 1979). In addition, leaves of older plants are more susceptible than similarly aged leaves from younger plants (Rotem, 1994). The causes of the observed changes in susceptibility with leaf age are not well known, but changes in membrane composition and more rapid degradation of membranes in older leaves are possible

Figure 1.1. Alternaria leaf blight lesions on carrot leaves.

causes in the susceptibility of tobacco to *A. alternata* (Fr.) Keissler infection (Barna and Györgyi, 1992). Alternaria diseases prefer low-sugar environments, and consequently, do not affect young leaves because of their high sugar and tannin concentrations (Ali and Roy, 1981). Alternaria diseases are also increased by factors such as moisture stress, mechanical damage, insect pests, or chemical damage, which stress the host plant (Rotem, 1994). For a review of the factors affecting susceptibility of plants to Alternaria diseases refer to Rotem (1994).

1.4.2 Cercospora Leaf Blight

Cercospora leaf blight (CLB) of carrots is caused by *Cercospora carotae* (Passerini) Solheim. The pathogen is classified in the *Fungi Imperfecti* (Class Deuteromycetes), and reproduces by asexual conidia. Cercospora leaf blight is less widely spread than ALB. It occurs on 91-96% of fields in Quebec, where 99% of plants are infected (Abraham et al., 1995), and in conjunction with ALB in Ontario. *Cercospora carotae* only infects species within the genus *Daucus* (Pryor and Strandberg, 2001), which includes carrot and wild carrot in Ontario. The pathogen overwinters on seed, wild or cull carrots, or on plant debris. Early seedling infection and lesion development are reported for *C. carotae*, but such symptoms are rare (Pryor and Strandberg, 2001). The main symptoms appear in early summer after conidia land on the plant, germinate, and directly penetrate the younger leaves. Lesions appear as small circular spots with a yellow halo and a tan to brown centre (Figure 1.2). As the season progresses, lesions expand and can coalesce, and petioles begin to be infected. Severe infections can lead to leaf death due to girdling of the petioles.

Figure 1.2. Cercospora leaf blight lesions on carrot leaves.

The combined effect of ALB and CLB is early leaf senescence and a reduction in the number of live leaves per plant, which can lead to leaf breakage during mechanical harvest, and many unharvested carrots remaining in the field. Methods of harvest that do not require healthy tops are available, but these are mainly used for processing carrots on mineral soil only. A disease severity of 20% for ALB can cause a significant yield loss in Ontario (Langenberg, 1975). A loss of leaf area due to ALB can also lead to decreased canopy photosynthesis in the last half of the growing season (Pryor and Strandberg, 2001). However, other evidence indicates no yield differences between a no fertilizer treatment and 1.1 $t \cdot ha^{-1}$ of 4-7.5-10.6 N-P-K fertilizer in Florida, despite 72% more leaf area damaged by ALB over the two month disease rating period (White et al., 1983).

The total losses to growers caused by both ALB and CLB can approach 100% if tops are completely destroyed and mechanical harvest is not possible. However, an extensive fungicide spray program can effectively control both diseases. Typically, using an integrated pest management (IPM) program, spraying of fungicides for leaf blight control begins when 25% of leaves are infected, which usually occurs in early summer for CLB and mid-summer for ALB, and continues every 7 to 10 days until a few weeks before harvest (Sutton and Gillespie, 1979). This IPM program can help to reduce the number of sprays by two or three, but a total of 5 to 10 sprays are still required for effective disease control. Incidence of ALB and CLB is high in even the most unfavourable weather conditions for the crop or disease in Ontario. Failure to apply fungicides can lead to total canopy destruction by harvest, and inability to harvest the crop (Figure 1.3).

Figure 1.3. Destruction of canopy at harvest caused by Alternaria and Cercospora leaf blight.

There have been many attempts over the past few decades to identify and breed resistance to these diseases into carrot cultivars. While some cultivars are less susceptible to both pathogens, complete resistance has not been identified (Strandberg et al., 1972; Lebeda et al., 1988; Simon and Strandberg, 1998), although some cultivars with less than 10% disease have been considered resistant (Gowda et al., 2000). More susceptible cultivars, such as 'Fontana', are still widely grown because of their superior yield and quality (McDonald et al., 2003). In addition, fungicides are effective at controlling leaf blight and preventing yield losses. However, there is increasing concern that fungicide resistance could develop in both pathogens, and this resistance would be easily preserved in the population due to their asexual reproduction. Moderate resistance of *A. dauci* to iprodione occurs in Spain (Fancelli and Kimati, 1991). Consequently, alternative methods of controlling leaf blight, such as crop nutrition, could be useful in reducing the number of fungicide applications, thereby reducing the selection pressure for resistant individuals and improving disease control.

1.4.3 Effects of Nitrogen on Alternaria and Cercospora Leaf Blight

Alternaria dauci

Most studies of N effects on the incidence and severity of ALB on field-grown carrots have involved studies of phosphorus (P) and potassium (K), in combination with N. Increasing the rates of N, P, and K fertilizer application in the greenhouse from half the optimum to the optimum rate of 100, 19, and 74 $mg \cdot kg^{-1}$ N, P, and K, respectively, results in a 23-30% reduction in ALB severity, a result possibly attributed to delayed leaf senescence (Vintal et al., 1999). This result is similar to the Florida study described earlier (White et al., 1983). Also, the incidence of *Alternaria solani* infection on tomato

decreases under high N nutrition in the greenhouse due to lower senescence and higher number of more resistant dark green leaves (Király, 1976). The severity of leaf blight of carrots decreases by 46% with increasing N rate from 28 to 90 $kg \cdot ha^{-1}$ under field conditions in Michigan (Warncke, 1996), and decreases by 24% with increasing N rate from 0 to 200% of the provincial recommendations under field conditions in Ontario (Westerveld et al., 2002). However, the studies did not attempt to examine the effects of N on CLB and ALB separately. There is no effect of increasing N application rate to carrots by 29% on ALB severity in Georgia (Langston and Hudgins, 2002). Early blight of potatoes caused *by A. solani* is also decreased by high N applications (Barclay et al., 1973; Soltanpour and Harrison, 1974; MacKenzie, 1981). The impact of N on each of the diseases and potential causes for the observed interactions remains ambiguous.

Several laboratory studies have shown some effect of N or N-containing compounds on *Alternaria* species. The concentration of zinniol, a phytotoxin produced by *A. dauci* and involved in pathogenicity, decreases from 2.3 to 1.5 $mg \cdot g^{-1}$ when the sucrose to asparagine ratio (C:N ratio) is decreased from 30:1 to 10:1 in laboratory cultures (Barash et al., 1981), a condition that would exist under low N fertilization in the field. The excess C under this condition may be used for the production of secondary metabolites by *A. dauci* (Barash et al., 1981). However, zinniol is not necessary for infection and pathogen spread to occur, and therefore cannot be the only factor involved in the N-ALB relationship (Barash et al., 1981). The number of conidia produced by *A. alternata* is lower at a C:N ratio of 40:1 compared to 15:1 or 5:1, but conidial survival and germination is higher at a C:N ratio of 15:1 compared to 5:1 (Montazeri and Greaves, 2002). Sporulation of Alternaria species in general is increased as leaf necrosis increases

(Rotem, 1994). Specific effects of N on *A. dauci* in the laboratory cannot currently be used to explain the effects of plant nutrition on disease severity in the field.

Cercospora carotae

The effects of N on CLB of carrots have not been extensively studied. In the greenhouse, 50% fewer conidia of *C. carotae* are produced, 33% fewer lesions on leaves develop per unit leaf area, and lesions are smaller in plants grown in pots flushed several times with distilled water compared with plants given a complete nutrient solution (Thomas, 1943). However, in the field, the N concentration of leaf tissue is not correlated with CLB incidence and severity (Tremblay and Charbonneau, 1993). Both CLB and ALB severity decrease with increasing N rate in Ontario, but the effect of N on each disease was not examined separately so it is unknown whether one or both of the diseases are affected (Westerveld et al., 2002). The phytoalexin, 6-methoxymellein (2-methyl-6-methoxy-8-hydroxy-3.4-dihydroisocoumarin), increases upon infection by *C. carotae* (Mercier and Kuc, 1997). The phytotoxin, cercosporin, is also produced by *C. carotae* (Assante et al., 1977). It is unknown how N nutrition of the leaf or of the pathogen affects 6-methoxymellein or cercosporin production.

Research reports on other *Cercospora* diseases is conflicting. High N decreases leaf spot of St. Augustinegrass caused by *C. fusimaculans* Atk. by 78% over low N treatments (McCoy, 1973), but high N increases gray leaf spot of corn caused by *C. zea-maydis* Tehon & Daniels by 50% (Caldwell et al., 2002), narrow brown leaf spot of rice caused by *C. oryzae* Miyake (amount of increase unknown)(Huber, 1980b), and leaf spot

in hot pepper caused by *C. capsici* Heald & Wolf by 200% (Vos and Frinking, 1997) over no N treatments. Causal mechanisms for these effects are unknown.

1.4.4 General Effects of N on Disease

Early research, mainly on cereals, suggests that increasing applied N results in higher susceptibility to both root and leaf diseases (Hare, 1966). However, a recent review of 418 studies revealed that disease severity is increased, decreased, or is unaffected by N in 168, 233, and 17 cases, respectively (Huber and Graham, 1999). Host defence against a foliar pathogen can be improved by nutrients in five main mechanisms (Colhoun, 1973; Huber, 1980b). In the first mechanism, the plant tolerates the disease by rapidly increasing leaf or root area and outgrowing the pathogen. For example, although take-all disease of wheat caused by *Gaeumannomyces graminis* (Saccardo) von Arx et Olivier is increased by NO_3-N, yields are improved under high NO_3-N conditions because of increased production of root tissues and adequate uptake of N (Huber, 1980a). In addition, coverage of barley leaves by powdery mildew, caused by *Erysiphe graminis* DC f.sp. *hordei*, increases from 10 to 20% when N fertilizer is applied, but yield increases by 50% (Last, 1962).

The second mechanism through which defence is improved by nutrition is by facilitating disease escape. This occurs through either altered maturity, which alters the timing of the most susceptible stage of plant growth, or altered environment during the most susceptible stage of growth, making it unfavourable for pathogen infection or development (Huber, 1980b). For example, potatoes under low N availability can partially escape late blight caused by *Phytophthora infestans* (Montagne) de Bary due to more rapid senescence and reduced late-season infection (Huber, 1980b). On the other

hand, wheat and carrots can partially escape powdery mildew caused by *Erysiphe graminis* DC f.sp. *tritici* E. Marchal (Tompkins et al., 1992) and Sclerotinia rot caused by *Sclerotinia sclerotiorum* (Lib.) De Bary (Couper, 2001), respectively, because the smaller canopies under N deficient conditions result in higher airflow around the leaves and lower humidity and leaf wetness, which do not provide a favourable environment for disease to develop. For Sclerotinia rot, high N causes decreased airflow through the canopy and increased humidity, and causes a corresponding increase in carpogenic germination, ascospore release, and foliar infection (Couper, 2001).

The third mechanism of nutrient effects on disease is improving host structural resistance. Often high N nutrition increases leaf succulence (Colhoun, 1973; Huber, 1980b). This occurs through the formation of larger cells with weaker cell walls due to rapid cell division, which can promote rapid pathogen penetration and infection (Huber, 1980b; Lampkin, 1990; Agrios, 1997). Lignification of cell walls and callose development are also affected by various nutrients that are required as cofactors, activators, or regulators of their production (Graham, 1983). Lignin content of rice plants decreases 53% under N fertilization as compared to a no N control (Matsuyama and Dimond, 1973). In contrast, carrot storage diseases are minimized by high N application rates (Mazur et al., 1994).

A fourth main mechanism that can explain disease-N relationships is a modification of physiological resistance. This occurs through either modification of the nutritional environment or inhibition of pathogenic activity (Huber, 1980b). Modification of the nutritional environment involves either the nutrient itself or the nutrient's effects on physiological reactions within the host tissue. For example, a plant may become more

resistant under low N conditions due to reduced availability of enzymes and amino acids required by the pathogen (Hare, 1966). Stewart's wilt of corn caused by *Xanthomonas stewartii* (Smith) Dowson is reduced under N deficient conditions due to the requirement of the pathogen for N in the xylem stream (McNew and Spencer, 1939).

Inhibition of pathogenic activity occurs through the production by the host of defence related compounds that inhibit the infection and spread of the pathogen. Many of the defence related compounds contain N or require N containing precursors and these include phenolic compounds such as alternariol and cercosporin, phytoalexins, flavonoids, and pathogenesis-related proteins (Huber, 1980b; Huber and Graham, 1999). These compounds accumulate around infection sites and their concentration is dependent on nutrient availability (Huber and Graham, 1999). For example, NO_3^- inhibits phenol metabolism whereas NH_4^+ increases Mn uptake leading to increased phenol metabolism (Huber and Watson, 1974). A reduction in the production and/or oxidation of these compounds in the host tissue can also suppress tissue necrosis, which may be necessary for the pathogen to survive (Király, 1964; Király, 1976). The concentrations of many phenolics and phytoalexins are increased by sub-optimal fertilization, such as stilbene, a phytoalexin involved in downy mildew resistance in grapes (Bavaresco and Eibach, 1987).

Finally, nutrients alter pathogen virulence by affecting the production and survival of inoculum, enzyme production by the pathogen, and the penetration and spread of the pathogen in the host (Huber, 1980b). For example, exogenous nutrients on the surface of onion leaves promote appressorium formation and penetration by *Botrytis cinerea* Persoon (Clark and Lorbeer, 1976). Under high N fertilization, amino acid

concentrations in leaf apoplasm and exudates are high, and this can affect spore germination and early fungal development (Marschner, 1995). Development of several pathogens is influenced by the nutrient content of the host or of a growth medium. For example, spore production by *Puccinia triticina* Eriks. in wheat is reduced when leaf N concentration is limiting (Robert et al., 2002), and *Colletotrichum truncatum* (Schweinitz) Andrus et Moore exhibits maximum conidiation at a C:N ratio of 15:1 and conidiation is reduced above or below this level (Jackson and Bothast, 1990). Eyespot and sharp eyespot of wheat caused by *Pseudocercosporella herpotrichoides* (Fron) Deighton and *Rhizoctonia cerealis* van der Hoeven, respectively, are increased by N because it stimulates enzymes involved in extracellular maceration of host tissues (Huber and Graham, 1999). Nutrients can also accumulate around infection sites and cause toxic effects on fungal pathogens, which causes limited further growth of the pathogen (Huber and Graham, 1999).

In summary, high N mainly suppresses the development of facultative parasites, by delaying leaf senescence and delaying infection (Király, 1976; Marschner, 1995). On the other hand, obligate parasites require assimilates produced by the host plant for survival, which are mainly supplied in larger concentrations under high N fertilization (Király, 1976; Marschner, 1995). In addition, the largest effects of host nutrition on the severity of disease occur in plants that are moderately susceptible (Huber, 1980b). Highly susceptible plants exhibit only minimal effects of nutrition. Because of the many mechanisms that are involved, every pathogen/host system responds differentially to N, and different environments and different host varieties can affect these responses (Gallegly and Walker, 1949; Huber, 1980b; Huber and Graham, 1999). Consequently,

every disease and environment situation must be assessed separately for responses to individual nutrients. Most diseases can be greatly reduced through proper host nutrition, but not eliminated (Huber and Graham, 1999).

1.5 Summary and Hypotheses

Previous research has shown a potential for high N application rates to reduce ALB severity, even though carrot yields generally do not respond to applied N. The use of N could lead to adverse side effects, such as excessive N leaching into ground and surface water. Such a strategy would reduce the need for fungicide sprays, which could cause damage to the natural ecosystem and may not always be effective for disease control, especially if weather conditions prevent timely application. Thus, this study was conducted to provide recommendations on the use of N for disease control. However, a greater understanding of the N dynamics of the carrot crop, its NUE, and its interrelationships with disease severity is required before recommendations can be established. The following hypotheses were tested in the greenhouse and in the field on mineral and organic soils, using two cultivars that differed in their susceptibility to leaf blight, over a three-year period.

1. Carrots exhibit high NUE.
2. The ALB susceptibility of different carrot cultivars and carrots grown at varying N application rates is influenced by the partitioning and status of N in the host plant and the effects of N on leaf senescence, whereas that of CLB is not.

The first hypothesis was tested by assessing the effects of N rate, method and timing on yield, quality, and storability in the field, and by tracking N uptake and partitioning over the growing season. In addition, rooting depth, rooting distribution, and the distribution of N uptake in the soil profile were examined. The second hypothesis was tested by assessing disease severity in the field and greenhouse using different N application rates and methods and relating disease severity to the N dynamics of the carrot crop and its effects on leaf senescence.

Chapter 2: Optimal Nitrogen Fertilization of the Carrot Crop in Ontario and Observations of Carrot Rooting Depth and N Uptake Dynamics.

Abstract

Recent provincial (Nutrient Management Act) legislation and the Kyoto Protocol have dictated a reduction in leaching of nitrate (NO_3^-) into ground and surface water and in the emission of greenhouse gases (e.g. N_2O) due to nitrogen (N) usage in agriculture. This experiment was designed to establish yield response curves for carrots on mineral and organic soils, which could be used to determine the minimum N requirements for the crop and test whether carrots exhibit high N use efficiency (NUE). Nitrogen was applied at 0, 50, 100, 150, and 200% of Ontario recommended N application rates (organic soil: 60 $kg \cdot ha^{-1}$ preplant; mineral soil: 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress) as ammonium nitrate. In addition, various N application sequences over three years and methods and timings within a year, including foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea, were applied to determine if common grower practices improve yield. Nitrogen application rate had no effect on the yield, quality, or storability of carrots grown on organic soil. On mineral soil there were no effects of applied N in the first year of the three-year study. In the second and third year on mineral soil, yield increased in response to increasing N, up to 200 and 91% of the recommended application rate, respectively. Yield declined above 91% of the recommended application rate in the third year due to a decrease in stand at higher N application rates. There were no effects of N on carrot quality or storability on

mineral soil. Altering the timing or sequence of N application had minimal effects on carrot yield or quality. Foliar N application improved yield in one of the three trials on each soil type. Preplant N was more important in determining yield potential in carrots than sidedress or foliar N application. Critical petiole sap NO_3-N concentrations were ineffective as an N monitoring tool for carrots, but critical soil NO_3-N concentrations could be established early in the season (31-36 $mg \cdot kg^{-1}$). Carrots were shown to be capable of extracting N from deep in the soil profile. The predominant N uptake period occurred in the months of August and September. There were no major differences between 'Idaho' and 'Fontana' carrots in their response to N application rate, or DM and N partitioning over the growing season. Carrots exhibit high NUE based on N applied, which is probably due to uptake of mineralized and residual N from the soil that is not accounted for in the calculation of NUE.

2.1 Introduction

Carrots require little applied N in temperate regions to achieve optimal yield (Hamilton and Bernier, 1975; Burdine and Hall, 1976; Venter, 1979; Wiebe, 1987; Evers, 1988; Rühlmann and Geyer, 1993; Warncke, 1996; Sanderson and Ivany, 1997; Gutezeit, 1999; Couper, 2001; Westerveld, 2002). There are also minimal effects of N application rate on quality (Burdine and Hall, 1976; Westerveld, 2002), or storability (Nilsson, 1979; Westerveld, 2002). Few studies have examined the reasons for the lack of yield effect, but high mineralization rates in temperate soils (Gutezeit, 1999; Zebarth et al., 2004) and deep and extensive rooting (Pietola and Smucker, 1998; Thorup-Kristensen and van den Boogaard, 1999) are possible causes. Furthermore, root crop yields benefit from an

increase in root:shoot ratio that is induced by N deficiency (Améziane et al., 1995; Villagarcia et al., 1998), and root crops in low N conditions are able to delay the filling of the storage root and focus on leaf growth early in the season (Heilmeier et al., 1994; Monson et al., 1994).

The recent impetus towards matching N fertilization with crop N removal under nutrient management legislation could cause problems for vegetable production if relevant N fertilization research is not conducted (OMAF, 2005). Beyond the practical needs of nutrient management there are many questions remaining about N utilization in carrots including N partitioning, rooting depth, and N uptake. While many studies have examined the effects of N on carrot yield and quality, few studies have examined the reasons for the lack of yield response, or the consequences of continual lack of N in the long term. The establishment of a yield response curve to applied N is essential for the creation of more efficient N fertilization recommendations and for improvement in the use of N monitoring as a method to increase N use efficiency (NUE). In addition, an examination of N response and root distribution in different cultivars could provide explanations for differences in Alternaria (ALB) and Cercospora (CLB) leaf blight susceptibility.

The purpose of this study was to test the following hypotheses:

1. Carrots exhibit high N use efficiency.
2. The ALB susceptibility of different carrot cultivars is influenced by the partitioning and status of N in the host plant, whereas that of CLB is not.

The first hypothesis was tested through evaluation of the effects of N application rate and method, and residual soil N on yield, quality, and storability of carrots grown on mineral and organic soil, and by examination of N uptake and rooting depth and distribution in field and greenhouse experiments. The second hypothesis was tested by comparing rooting depth and distribution, the distribution of N uptake, and N partitioning over the season between two cultivars that differed in their susceptibility to ALB and CLB.

2.2 Materials and Methods

2.2.1 Nitrogen Rate in the Field

Field experiments were conducted on mineral and organic soils on the Holland/Bradford Marsh (44°15'N 77°90'W), Ontario, Canada at or near the University of Guelph, Muck Crop Research Station from 2002 to 2004. The organic soil (typic humisol - muck) contained 60-80% organic matter and had a pH of 6.1-6.8. The mineral soil (dark grey gleysol-Granby sandy loam) contained 1.0-3.5% organic matter, 90% sand, and had a pH of 7.9-8.4. Cultivars 'Idaho' and 'Fontana' were used in all field experiments. For the three-year experiments, carrots were seeded using a Stan Hay precision seeder into organic soil on 24 May (2002), 2 June (2003), and 21 May (2004) and into mineral soil on 3 June (2002), 2 June (2003), and 20 May (2004). Each experimental unit in the organic soil site in 2002 consisted of eight hills (four hills·cultivar^{-1}), 5 m in length, 20 cm high, spaced 86 cm apart, and a seeding rate of 80 seeds·m^{-1}. Each experimental unit in the mineral soil plot in 2002 consisted of 16 hills (eight hills·cultivar^{-1}), 10 m in length, 20 cm high, spaced 86 cm apart, and a seeding rate

of 80-100 seeds·m of row^{-1}. Mineral soil plots were re-hilled twice during the season in all three years. Nitrogen was applied at 0%, 50%, 100%, 150%, and 200% of the Ontario recommended N rates (OMAF, 2002) to the entire experimental unit area in 2002 using ammonium nitrate. The recommendations were 60 kg·ha^{-1} N applied preplant on organic soil, and 110 kg·ha^{-1} N split 66% preplant and 33% sidedress on mineral soil. For 2003 and 2004 each experimental unit was split in half. In 2003 in one half, the same N rates were applied as in 2002 (Annual fertilizer section). In the other half, no N was applied to identify any effects of residual N from the 2002 season (Alternating fertilizer section). In 2004, both halves received the same N rate as was applied in 2002. This allowed for a comparison between carrots given the same N rate for three consecutive years (Annual fertilizer) to those given N for one year following no N application (Alternating fertilizer). Carrots were grown on the same site for three years in an attempt to reduce residual N levels and increase the N response of carrots over time. For the 0 N treatment, both halves received no N fertilizer in all three years. Consequently, only one sample was collected for all assessments of this treatment and assumed to represent both sections. Additional treatments of different N sequences over three years and timings within a year were included in these trials and these treatments and results are summarized in Appendix 1.

At three times during the growing season (55-66 days after seeding (DAS), 87-96 DAS, and 116-126 DAS), 16 petioles from recently matured leaves were collected at random within the middle rows of each plot for NO_3-N analysis. Samples were only taken from the annual fertilizer sections because of the higher probability of yield response to N fertilizer in these sections. The petioles were separated into four groups of

four petioles and sap was extracted from each group using a hand-held garlic press. The sap was tested for NO_3-N content using a Horiba 'Cardy' Model C-141 NO_3^- meter. At the second sampling date in each year (third on organic soil in 2003) 30 petioles were collected. Half the number of petioles were used for Cardy meter NO_3-N analysis and half were dried at 70^{o}C for 48 h and sent to the University of Guelph, Soil and Nutrient Laboratory (2002 and 2003) and A&L Laboratories East Inc. (2004) for total N (2002 and 2004) and NO_3-N analysis (all three years) to calibrate the meter and test its accuracy. Only three replications were used in 2002 and 2003 for laboratory analysis. Total N concentration was determined by automated dry combustion procedures by both laboratories (Shepers et al., 1989). Nitrate-N concentrations were determined by the University of Guelph, Soil and Nutrient Laboratory through KCl extraction and automated colourimetric analysis (Maynard and Kalra, 1993) and by A&L Laboratories East, Inc. through microwave digestion and inductively coupled plasma-emission spectrometry (ICP) (Anonamous, 1997).

Soil samples were collected from each block prior to the 2002 season and from the recommended rate treatment after harvest in 2002. Thereafter, prior to and following each season, soil samples were collected from the annual fertilizer section of the plots. Each soil sample consisted of eight to ten soil cores 25 to 30 cm deep. In addition, at the same sampling dates as the sap NO_3^- tests, soil samples were collected, dried at 70^{o}C for 48 h and tested at a later date for NO_3-N content using the Cardy meter according to the procedures described by Westerveld et al. (2005). At the second sampling date (third for organic soil in 2003), half of the samples were frozen instead of dried and sent to the laboratories described above for total N and NO_3-N analysis for meter calibration and to

determine its accuracy. In 2004, prior to and following the growing season, deep soil samples were collected by taking eight to 10 soil cores from around the perimeter of a single 60 cm wide hole 90 cm deep from three replications of the 0, 100, and 200% of the recommended rate treatments. Samples were collected from two depths (30-60 cm deep and 60-90 cm deep) by taking cores at 45^{o} angles from the sides of the hole, dried at 70^{o}C for 48 h and sent to A&L Laboratories East, Inc. for total N and NO_3-N analysis. For soil analysis, the University of Guelph, Soil and Nutrient Laboratory used automated dry combustion for total N (McGill and Figueiredo, 1993) and KCl extraction and automated colourimetric analysis for NO_3-N (Maynard and Kalra, 1993). A&L Laboratories East, Inc. used automated dry combustion for total N and Cd reduction and automated colourimetric analysis for NO_3-N and NH_4-N (Jones, 1999). Total available N preplant was calculated for 2004 data only (3 treatments, 3 replications) by adding preplant-applied N to N available from NO_3^- in each 30 cm section of soil, which was calculated by assuming 1 ha 30 cm deep has a dry weight of 4,000,000 kg for mineral soil and 1,500,000 kg for organic soil (Westerveld, 2002) and multiplying soil NO_3^- concentration by this number. Soil NH_4^+ concentrations were not included in the calculation because the concentrations were low and were relatively constant across all N application rates tested.

In 2004, the number of seedlings per metre was assessed on 11 June and 22 June on mineral soil and 11 June on organic soil by counting a random 2.3 m section in the middle rows of both cultivars. These assessments were conducted on the N rate treatments in the annual fertilizer sections of the plots. The assessments were to document observed seedling death.

2.2.2 Foliar Nitrogen

Carrots were seeded using a Stan Hay precision seeder on 24 May (2002), 26 May (2003), and 26 May (2004) into organic soil, and 28 May (2002), 2 June (2003), and 1 June (2004) into mineral soil. The plots were located in the same two fields as the N rate experiments above, but were conducted on separate locations within those fields in each year. Plots consisted of four hills (two hills·cultivar^{-1}), 5 m in length, 20 cm high, spaced 86 cm apart, and with a seeding rate of 80 seeds·m^{-1}. Plots on mineral soil were re-hilled twice during the season. The treatments included a no N control (all plots), three N rates (0, 50, and 100% of the provincial recommended N rates (OMAF, 2002)) each given, in addition to the N application rates, bi-weekly foliar sprays of 2 kg·ha^{-1} N as urea once tops filled 75% of the inter-row space (2002 no surfactant, 2003 and 2004 with Agral 90 surfactant at 1 mL·L^{-1}), no N preplant plus foliar sprays without surfactant (2003 and 2004), the recommended rate all sidedressed (2002, 2003 mineral soil only, 2004), the recommended N rate split 50% preplant and 50% sidedressed (all plots), 50% of the recommended rate all sidedressed (2004 organic soil only), and 200% of the recommended rate all sidedressed (2003 and 2004 mineral soil only). Foliar N was applied using a Solo hand-pumped backpack sprayer. Granular N was applied as ammonium nitrate.

At three times during the growing season (52-72 days after seeding (DAS), 84-95 DAS, and 112-126 DAS) eight petioles from recently matured leaves from each of the foliar N treatments and the no N control treatment were collected, split into two groups of four, and tested for sap NO_3-N concentration using the Cardy meter as previously

described. At the same time soil samples were collected and tested using the Cardy meter as previously described. Soil samples were also collected from each block before seeding in 2003 and 2004, frozen, and sent to a laboratory for total N and NO_3-N analysis.

Carrots from the annual fertilizer section of the N rate experiment were hand-harvested from one (organic 2003 and 2004) and two (organic 2002, and mineral all three years) 2.3 m sections of the middle rows of each cultivar and treatment on 18 Oct. (2002), 27 and 28 Oct. (2003), and 21 Oct. (2004) on organic soil, and 24 Oct. (2002), 23 and 24 Oct. (2003), and 26 Oct. (2004) on mineral soil. Carrots from the additional treatments, the foliar N experiments, and the alternating fertilizer sections were harvested from one 2.3 m section of row for all years and both soil types. For all treatments and experiments carrots were assessed for total yield, marketable yield, weight per root, stand per metre, and were separated into three grades (diameter>4.4 cm, 2.0-4.4 cm, and culls (including carrots <2.0 cm)). For four of the experimental units in the foliar N experiment on mineral soil in 2004, the harvested samples were taken from < 2.3 m of row because thieves had removed the majority of the carrots from the experimental units. The removal occurred close to harvest and would not have had an impact on carrot development. In these cases, the remaining sections of row were measured and the measurements were factored into the calculation of yield results. Marketable carrots from the annual fertilizer section of the N rate experiments were placed into cold storage (1^oC) for six months. After storage carrots were assessed for percent weight loss, culls, and total loss by weight. Weather data from the University of Guelph, Muck Crops Research Station are

summarized in Table 2.1. The field experiments were arranged in a split-block design with cultivar as the main plot and N treatment as the sub-plot and four replications.

2.2.3 Root Depth and Nitrogen Uptake

A study was conducted in the winter and spring of 2003 and the fall and winter of 2003 and 2004 in the greenhouse to examine depth and distribution of carrot roots. 'Idaho' and 'Fontana' carrots were seeded into 98% pure silica sand in 150 cm deep and 10 cm diameter PVC pipes, which were split in half longitudinally and re-attached using hose clamps and silicone calking (Figure 2.1). There were four one-pot replications of each cultivar/treatment combination. Ten seeds were planted in each pipe, which were thinned to one plant per pot upon germination. The pipes were irrigated with tap water daily using drip irrigation. All pipes received 1 L of 50% nutrient solution lacking N as described by Hoagland and Arnon (1938) weekly. Three rates of N were applied in the nutrient solution by adding ammonium nitrate at a rate equivalent to 50%, 100%, and 200% of the N required for a 50% Hoagland solution. The experiment was arranged in a randomized complete block design. One replication of the winter/spring 2003 experiment was not assessed due to accidental disruption of the rooting system in the pots during transport.

After six months of growth the pipes were split in half longitudinally for assessment of depth of fibrous roots. In addition, the column of sand was split into five sections of 30 cm and each section was submerged into water in an 18-mesh sieve and rinsed to separate the sand from the fibrous roots. The tops, storage root, and fibrous

Figure 2.1. Carrots grown in 150 cm deep, 10 cm diameter PVC pipes filled with silica sand and drip irrigated.

Table 2.1. Monthly mean temperature and rainfall at the University of Guelph, Muck Crops Research Station from 2002 to 2004 as compared to 10-year means.

Month	2002		2003		2004		10-year mean temp. (°C)	10-year mean rainfall (mm)
	Mean Temp. (°C)	Rainfall (mm)	Mean Temp. (°C)	Rainfall (mm)	Mean Temp. (°C)	Rainfall (mm)		
May	9.9	113	12.2	105	12.4	108	12.3	89
June	18.2	106	17.3	75	16.3	50	18.0	87
July	21.7	76	19.9	29	19.3	102	19.9	73
Aug.	19.6	18	20.4	81	17.8	103	19.2	62
Sept.	17.5	40	15.0	110	16.6	25	15.4	77
Oct.	7.2	49	8.0	78	9.1	26	8.9	65

roots from each of the 30 cm sections were collected, dried at 70°C for 48 h, and dry weights determined.

In the fall of 2004 and winter of 2005, the PVC pipes were filled with Sunshine 2 potting mix (70-80% peat, perlite, dolomitic limestone, gypsum, and wetting agent; JVK, St. Catherines, ON); a mixture that lacks added nutrients. 'Idaho' and 'Fontana' carrots were seeded into the pipes as described above. The pipes were drip irrigated at the surface of the growing mix with a complete 25% Hoagland solution every two days from seeding until final assessment. When the majority of the storage roots were between 1.5 and 2.5 cm diameter, a solution of 500 $mg \cdot L^{-1}$ N was prepared by dissolving 10% enriched ^{15}N KNO_3 in distilled water. The PVC pipes were divided into three groups, and in each group a single hole was drilled at one of three different depths, 30, 80, and 130 cm below the crown of the plant. A 50 mL syringe was used to inject 50 mL of the KNO_3 solution into the drilled holes. Four weeks later the pipes were dismantled and the plants assessed for depth of the fibrous roots. It was not possible to separate the fibrous roots from the potting mix and determine a dry weight as described in the sand experiment. The fibrous root system was assessed by counting the number of fibrous roots that passed through the 30, 80, and 130 cm depths and by counting the number of fibrous roots that were visible around the perimeter of the soilless mix column every 10 cm beginning 5 cm below the crown. Since roots did not reach the 80 cm depth in some pots, and the 130 cm depth in most of the pots, pots injected with KNO_3 at this depth were combined with pots injected at the 80 cm depth and treated as a single treatment. The plant top in each of the pots was split in half, into old and new leaves, and the two leaf sections and the storage roots were dried at 70°C for 48 h and then weighed. The dried samples were coarsely

ground using a mortar and pestle and mixed. A 1-g portion of each sample was ground into a fine powder using a shaker-ball mill. A 5-10 mg portion of each sample was weighed on a microgram scale, placed into tin capsules, folded into small cubes that were less than 6 mm diameter, placed into a 96-well microtitre plate, and sent to the UC Davis Stable Isotope Facility for total N and atom percent ^{15}N analysis. Recovery of ^{15}N enriched fertilizer was calculated using the following equation:

$$\text{Recovery} = \frac{[(\text{atom \% } ^{15}\text{N of sample}) - 0.366]}{[(\text{atom \% } ^{15}\text{N of fertilizer}) - 0.366]} \times \text{N in sample}$$

2.2.4 Nitrogen Uptake of Cultivars

On 30 May 2003, 'Idaho' and 'Fontana' carrots were seeded at 10 seeds per pot into 15-cm diameter, 20 cm deep pots filled with ASB potting mix (>95% Peat, nutrient and pH adjusted; ASB Greenworld Inc., Mt. Elgin, ON). There were 16 pots per cultivar, two pots for each of two ^{15}N application dates and four replications of each. The pots were placed outside on a gravel surface at the University of Guelph – Muck Crops Research Station in a randomized complete block design to simulate natural field conditions. Upon germination the pots were thinned to one plant per pot. The pots were fertilized biweekly by adding 500 mL of a fertilizer solution prepared by dissolving 1.7 g 20/20/20 fertilizer per litre of tap water. On 12 Aug. (74 DAS) half of the pots were fertilized with 1.2 g of 10% enriched ^{15}N KNO_3 dissolved into 500 mL of distilled water. The other half of the pots was fertilized using the same procedures on 4 Sept. (97 DAS). The pots fertilized on 12 Aug. were assessed on 4 Sept. for fresh weight of the old leaves, new leaves, and storage root. The samples were oven dried at 70^{o}C for 48 h and assessed for dry weight. The pots fertilized on 4 Sept. were assessed on 25 Sept. using the same procedures described above. Samples from the two pots from each replicate were

combined for dry weight and ^{15}N analysis. Each sample was ground, weighed, and analysed for ^{15}N content as described above.

2.2.5 Statistical Analysis

An analysis of variance was performed on each data set to partition the variance into treatment, block, cultivar, soil type, and year effects, where applicable, and to identify interactions among these effects. Data from the N rate treatments in the field and the greenhouse were analysed by linear and quadratic regression analysis. The entire data set for each assessment was assessed for normality using the Shapiro-Wilk test of residuals. When data did not fit a normal distribution, data were natural log transformed for statistical analysis and reported data represent untransformed values. Outliers were identified using Lund's test of standardized residuals (Lund, 1975). Peak values using quadratic regression equations were determined by setting the slope to zero and solving the first derivative of the regression equation. Fisher's Protected LSD Test was used for mean separation in all non-rate treatments and for cultivar comparison. Critical NO_3-N concentrations were established by determining the lowest N rate that maximized total yield and using that N rate to solve the corresponding NO_3-N regression equation, or, in the cases where no linear relationship was identified, choosing the lowest NO_3-N concentration. Meter readings were compared to laboratory analysis results using linear correlation analysis. Data were analyzed using the PROC GLM, PROC CORR, PROC PLOT, and PROC Univariate procedures of SAS version 8.0 (SAS Institute, Cary NC) and the linear models sections of Statistix V.4.1. A type I error rate of 0.05 was set for all statistical tests. Significant regression equations from Chapter 2 are listed in Appendix 3.

2.3 Results

2.3.1 Nitrogen Rate in the Field

Since there were no cultivar/treatment interactions, both cultivars responded to N application rate in a similar manner and combined data were reported for all yield and quality results. Overall, total yield of both cultivars was similar (Appendix 2).

Total yield of carrots grown on organic soil was not affected by N application rate over the three years of the trial in either section of the plots (Table 2.2). Applied N did not affect the yield of carrots grown on mineral soil in the annual fertilizer section in the first year of production, but it did increase yields in the second and third years (2003 and 2004) of the trial (Table 2.2). Yield increased up to 200% of the recommended rate in 2003 and up to 90.8% of the recommended rate in 2004 in the annual fertilizer section (Table 2.2). In the alternating fertilizer section of the plots in 2003, which received no N in 2003, yield increased with increasing N rate applied in 2002. However the slope of the yield curve was less in the alternating fertilizer section than in the annual fertilizer section (Table 2.2). In the alternating fertilizer section in 2004 on mineral soil, total yield increased with increasing N rate up to 99.1% of the recommended rate and then decreased at higher N rates (Table 2.2). In the annual fertilizer section, the mean total yield over the three years increased with increasing N rate up to 102.4% of the recommended rate and then decreased at higher N rates (Table 2.2). Mean yields in the annual mineral soil plots were highest in 2003 and lowest in 2004. Total yield decreased each year of the experiment in the annual fertilizer section on organic soil (Table 2.2). Total yields were below provincial average yields (78-90 $t \cdot ha^{-1}$ (OMAF, 2004)) for all

Table 2.2. Effect of annual or alternating nitrogen (N) application rate on total yield of carrots grown on two soil types for three years (average of two cultivars).

N rate (% of recommended)[z]		Total Yield (t·ha^{-1})					
		2002	2003		2004		3-YR Mean[x]
			Annual[y]	Alter-nating[y]	Annual	Alter-nating	
Mineral Soil							
0		47.7	36.1[w]	36.1	38.8[v]	38.8	40.9
50		45.5	47.6	39.4	47.1	51.7	46.7
100		52.3	50.9	40.4	50.9	54.0	51.4
150		40.0	54.7	47.1	47.0	48.2	47.2
200		43.4	54.6	47.1	31.6	39.9	43.2
Mean		45.8	48.8	42.0	43.1	46.5	45.9
Significance	L	NS	***	*	NS	NS	NS
	Q	NS	NS	NS	***	***	***
	R^2	--	0.60	0.30	0.58	0.65	0.49
Organic Soil							
0		95.6	78.7	78.7	71.7	71.7	82.0
50		97.0	78.8	80.1	72.7	69.5	82.8
100		95.3	79.1	76.3	69.5	71.8	81.3
150		94.4	74.4	77.6	72.1	72.5	80.3
200		92.1	74.7	78.5	71.7	71.9	79.5
Mean		94.9	77.1	78.2	71.5	71.5	81.2
Significance	L	NS	NS	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.
[y] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.
[x] Average of annual fertilizer sections only.
[w] One outlier removed for reported means and statistical analysis.
[v] One experimental unit removed due to localized flooding on mineral soil.
[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

three years on mineral soil. However, reported average yields are partly from organic soil, and mineral soil yields are typically lower. On organic soil, mean total yields were above provincial averages in 2002 and declined to slightly below average in 2004 (Table 2.2).

Nitrogen application rate had an effect on early season survival of carrots. The number of live seedlings per metre in early June 2004 decreased with increasing N rate on mineral soil (Table 2.3). The stand 11 days later was thinner, especially in the high N treatments. The number of visible dead seedlings at the early assessment date increased with increasing N rate, but could not account for the majority of the missing plants in the high N treatments (Table 2.3). There was no effect of N rate on stand or the number of visible dead seedlings per metre early in the season on organic soil (Table 2.3). Although both cultivars exhibited similar effects of N on stand early in the season, 'Idaho' had better seedling emergence than 'Fontana' at both assessment dates (Appendix 2).

Carrot stand at harvest increased slightly with increasing N rate in 2002 on both soil types up to a maximum at 73.8% of the recommended rate on mineral soil and 58.0% of the recommended rate on organic soil, and then decreased slightly at N rates above the optimum (Table 2.4). In 2003 on mineral soil in the annual fertilizer section, and in 2004 in both sections, stand at harvest decreased with increasing N rate. Carrot stand at harvest was much higher in 2003 than in the other two years on mineral soil (Table 2.4). On organic soil in 2003 and 2004 there was no effect of N rate on stand at harvest (Table 2.4). In most cases 'Idaho' had a denser stand at harvest than 'Fontana' on both soil types (Appendix 2).

Table 2.3. Effect of nitrogen (N) application rate on carrot stand in the seedling stage on mineral and organic soil in 2004 (average of two cultivars; seeding rate 80 seeds·m^{-1}).

N rate (% of recommended)[z]		Stand (plants·m^{-1})				
		Mineral Soil			Organic Soil	
		Jun 11 Live	Jun 11 Dead[y]	Jun 22 Live	Jun 17 Live	Jun 17 Dead[y]
0		50.3	0.4	49.6	49.7	0.7
50		47.2	1.8	46.7	46.1	0.6
100		39.3	3.6	39.3	45.5	0.4
150		36.8	3.0	35.3	47.2	0.8
200		27.1	3.3	18.9	50.3	0.6
Significance	L	***	**	***	NS	NS
	Q	NS	NS	NS	NS	NS
	R^2	0.63	0.37	0.73	--	--

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Plants visible but dead at the time of assessment.

NS,*,**,*** Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table 2.4. Effect of annual and alternating nitrogen (N) application rate on stand at harvest of carrots grown on two soil types for three years and seeded at a rate of 80 seeds·m^{-1} (average of two cultivars).

N rate (% of recommended)[z]		Stand at Harvest (roots·m of row^{-1})					
		2002	2003		2004		3-year Mean
			Annual[y]	Alter-nating	Annual	Alter-nating	
Mineral Soil							
0		35.1[w]	74.1	74.1	48.8	48.8	52.7
50		41.7	71.2	66.5	46.4	41.9	53.1
100		39.9	68.3	65.8	34.7	31.4	47.6
150		32.5	58.6	65.0	28.9	29.4	40.0
200		30.2	45.1	57.0	17.4	20.5	30.9
Mean		35.9	63.5	65.7	35.2	34.4	44.9
Significance	L	*	***	NS	***	***	***
	Q	*	NS	NS	NS	NS	*
	R^2	0.39	0.57	--	0.80	0.62	0.75
Organic Soil							
0		52.3[w]	59.9	59.9	46.9	46.9	53.0
50		62.7	64.7	56.2	44.8	46.1	54.6
100		60.6	61.5	49.4	44.1	41.9	55.4
150		59.4	56.2	52.9	43.5	49.8	53.0
200		53.8	56.9	53.2	48.3	45.1	53.0
Mean		57.8	59.8	54.3	45.5	46.0	54.4
Significance	L	*	NS	NS	NS	NS	NS
	Q	*	NS	NS	NS	NS	NS
	R^2	0.42	--	--	--	--	--

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.

[x] Average of annual fertilizer sections only.

[w] One outlier removed for the reported means and statistical analysis.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

The effect of N application rate on marketable yield followed the same pattern as total yield, but declined more over the three years compared to total yield (Appendix 2). Weight per root was only influenced by N application rate when stand was affected, since there was a strong negative correlation between weight per root and stand at harvest in all years (mineral soil 3-yr mean r=-0.86; organic soil 3-yr mean r=-0.82) (Appendix 2). The distribution of carrots among the three size and quality grades was mainly influenced by weight per root differences, and the proportion of carrot roots that were culls increased with increasing N rate in 2004 on mineral soil due to an increase in forking and aster yellows caused by the same factor that decreased stand (Appendix 2). There was also an increase in culls with increasing N application rate in the alternating N rate section of the plots due to more forking and splitting at the high N application rates (Appendix 2). There were no differences in the cultivar response to N application rate, except that 'Fontana' generally had higher weight per root than 'Idaho', and 'Idaho' generally had a higher proportion of culls due to small carrots on mineral soil (Appendix 2).

With one exception there was no effect of N rate in the field on losses in storage on both soil types (Table 2.5). However, there was a decrease in the number of cull roots due to rots and sprouting in storage with increasing N rate on mineral soil in 2003 (Table 2.5). 'Idaho' carrots exhibited more weight loss in storage than 'Fontana' carrots in most cases, but 'Fontana' carrots exhibited more losses due to culls in storage in most cases (Appendix 2).

Sap NO_3-N concentrations, as measured by a Cardy NO_3^- meter, generally increased with increasing N rate on mineral soil, especially in the early and mid-season sampling dates for both cultivars (Table 2.6). 'Fontana' carrots generally had higher sap

Table 2.5. Effect of annual nitrogen (N) application rate on the decrease in weight and marketable roots after six months of cold storage for carrots grown in organic and mineral soil for three years (average of two cultivars).

N rate (% of recommended)[z]		Weight Loss (%)			Cull Losses (%)			Total Loss (%)		
		2002	2003	2004	2002	2003	2004	2002	2003	2004
Mineral Soil										
0		6.8	8.8	9.6	0.0	2.6[y]	1.2	6.8	11.4	10.8
50		6.4	7.8	10.5	2.0	2.6	2.1	8.4	11.4	12.6
100		6.2	7.9	10.7	0.0	1.5	0.1	6.2	9.4	10.8
150		7.0	7.8	11.3	0.1	1.6	0.7	7.1	10.9	12.0
200		6.7	6.8	8.4	0.4	1.4	0.5	7.1	8.2	9.0
Significance	L	NS	NS	NS	NS	*	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	0.28	--	--	--	--
Organic Soil										
0		4.4	7.0	5.7	1.8	7.0	1.0	6.3	13.9	6.8
50		4.6	7.1	5.7	3.4	8.2	2.5	8.0	15.3	8.2
100		4.2	7.5	5.5	4.6	5.6	1.5	8.8	13.1	7.1
150		3.8	7.5	5.2	2.0	9.2	2.3	5.8	16.7	7.6
200		4.1	9.0	6.0	2.7	9.9	1.3	6.8	18.9	7.3
Significance	L	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--	--	--	--

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.
[y] Two outliers removed.
NS,*,**,*** Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table 2.6. Effect of annual nitrogen (N) application rate over three years on sap nitrate-N (NO_3-N) concentration early (55-66 days after seeding (DAS)), mid-season (87-96 DAS), and late (116-126 DAS) of carrots grown on mineral soil.

N rate (% of recommended)[z]		Sap NO_3-N Concentration ($mg \cdot kg^{-1}$ fw)						Laboratory Results[y]	
		Idaho			Fontana				
		Early	Mid-Season	Late	Early	Mid-Season	Late	NO_3-N $mg \cdot kg^{-1}$	Total N (%)
2002	0	290	150	220	1260	310	110	280[x]	0.84[x]
	50	430	220	110	990	420	110	480	0.83
	100	420	330	240	1750	370	90	790	0.90
	150	870	360	210	2790	960	140	1100	1.02
	200	830	430	190	2060	540	130	2200	1.12
Significance	L	**	*	NS	**	NS	NS	**	**
	Q	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	0.39	0.29	--	0.37	--	--	0.49	0.44
2003	0	250	210[x]	200	620	220	170	3	--
	50	440	240	220	780	400	220	110	--
	100	540	220	200	1030	460	240	60	--
	150	550	420	204	1280	960	370	690	--
	200	720	380	220	1290	1130	500	1130	--
Significance	L	*	*	NS	**	**	***	**	--
	Q	NS	NS	NS	NS	NS	NS	NS	--
	R^2	0.31	0.33	--	0.42	0.42	0.63	0.68	--
2004	0	240[w]	130	200	450	160	180	11	0.63
	50	500	150	260	1150	190	280	74	0.69
	100	810	130	190	2120	220	260	50	0.67
	150	980	210	400	2210	460	450	346	0.91
	200	1370	200	270	1600	550	510	665	0.92
Significance	L	***	*	NS	*	***	**	***	***
	Q	NS	NS	NS	*	NS	NS	*	NS
	R^2	0.76	0.29	--	0.45	0.61	0.39	0.74	0.58

[z] Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.

[y] Samples collected from Idaho carrots during the second sampling date for all three years and sent to a laboratory for total N and NO_3-N analysis.

[x] Outliers removed for statistical analysis.

[w] Due to sensor problems one replication removed for statistical analysis.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

NO_3-N concentrations than 'Idaho' at the first two sampling dates in all three years, but were similar to 'Idaho' at the late sampling date (Table 2.6).

On organic soil there was no increase in sap NO_3-N concentration for 'Idaho' carrots except at the late sampling date in 2004 (Table 2.7). For 'Fontana', there was an increase in NO_3-N concentrations with increasing N rate mid-season in 2002, late in the season in 2003, and at all three sampling dates in 2004 (Table 2.7).

Sap NO_3-N concentrations in 'Idaho' petioles were correlated with tissue NO_3-N and total N concentrations as determined by laboratory analysis in all three years on mineral soil (Table 2.8). However, some variability in a few sap NO_3-N results as determined by the laboratory occurred, especially on mineral soil, and may not have been representative of actual NO_3-N concentrations. For example, the mean of three sap NO_3-N samples in 2003 at the low N rate was 3 $mg \cdot kg^{-1}$, which is much below what is considered adequate for plant growth. The conversion factors between laboratory and Cardy meter results, which could be used to equate Cardy meter readings to laboratory results, were also highly variable (Table 2.8). Sap NO_3-N concentrations were correlated with laboratory tissue total N and NO_3-N results from 'Idaho' carrots on organic soil in 2002 and 2003, but not in 2004 (Table 2.8). Laboratory results and the conversion factors between laboratory results and the Cardy NO_3^- meter readings were highly variable (Table 2.8).

Critical NO_3-N concentrations were variable among the years and soil types (Table 2.9). The critical levels reported for organic soil can only be assumed to be maximum critical concentrations because optimal yield may have been achieved under lower N fertility levels than occurred in the no N treatment in all three years. 'Idaho'

Table 2.7. Effect of annual nitrogen (N) application rate over three years on sap nitrate-N (NO_3-N) concentration early (55-66 days after seeding (DAS)), mid-season (87-96 DAS), and late (116-126 DAS) of carrots grown on organic soil.

N rate (% of recommended)[z]		Sap NO_3-N Concentration ($mg \cdot kg^{-1}$)						Laboratory Results[y]	
		Idaho			Fontana				
		Early	Mid-Season	Late	Early	Mid-Season	Late	NO_3-N $mg \cdot kg^{-1}$	Total N (%)
2002	0	790	460	60	1040	560	280	1240	0.90
	50	1260	620	70	1160	540	160	1790	0.96
	100	1460	900	80	1470	670	460	2290	1.08
	150	1130	620	70	1000	600	240	1550	0.96
	200	1340	560	120	1460	1140	320	2690	1.09
Significance	L	NS	NS	NS	NS	*	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	0.24	--	--	--
2003	0	350	260	170	600	390	210	630	--
	50	390	210	170	800	710	420	420	--
	100	450	240	210	1050	860	470	550	--
	150	500	350	200	850	840	440	1220	--
	200	600	370	160	940	690	490	1210	--
Significance	L	NS	NS	NS	NS	NS	*	NS	--
	Q	NS	NS	NS	NS	NS	NS	NS	--
	R^2	--	--	--	--	--	0.23	--	--
2004	0	890	170	160	990	250	220	149	0.90[x]
	50	830	170	120	1500	400	300	150	0.87
	100	750	350	120	2150	630	420	194	0.91
	150	1220	200	170	1790	550	480	357	0.88
	200	1190	350	220	2310	910	760	697	1.01
Significance	L	NS	NS	*	*	**	***	***	**
	Q	NS	NS	*	NS	NS	NS	**	NS
	R^2	--	--	0.43	0.30	0.36	0.67	0.61	0.46

[z] Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.

[y] Samples collected from Idaho carrots during the second sampling date in 2002 and 2004 and the third sampling date in 2003 and sent to a laboratory for total N and NO_3-N analysis.

[x] One outlier removed for statistical analysis.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table 2.8. Linear correlation statistics and conversion factors for the comparison of Cardy meter sap nitrate-N (NO_3-N) readings to laboratory total nitrogen (N) and NO_3-N concentrations at a mid- or late-season sampling date for 'Idaho' carrots grown on organic and mineral soil.

Soil	Year	Linear Correlation Statistics					
		Total N[z]			Nitrate-N[z]		
		P	r	Conversion[y]	P	r	Conversion[y]
Organic	2002	0.0002	0.82	0.00219 (0.00128)[x]	0.0006	0.78	2.789 (1.742)
	2003	--	--	--	0.0007	0.77	4.394 (3.638)
	2004	0.5103	0.16	0.00522 (0.00237)	0.1229	0.36	1.418 (0.970)
Mineral	2002	0.0013	0.75	0.00394 (0.00132)	0.0002	0.82	3.296 (2.272)
	2003	--	--	--	0.0082	0.65	1.056 (1.464)
	2004	0.0009	0.68	0.00489 (0.00125)	0.0014	0.66	1.176 (1.461)

[z] Comparison between Cardy meter sap NO_3-N readings and laboratory total N and NO_3-N concentrations.
[y] Equation: Cardy sap NO_3-N x conversion factor = Laboratory total N or NO_3-N concentrations (dry weight basis).
[x] Reported as mean (standard error).

Table 2.9. Sap nitrate-N (NO_3-N) concentrations for each cultivar that correspond with the N rate producing the maximum yield for carrots grown on organic and mineral soil from 2002 to 2004.

Soil Type	N rate with maximum total yield (% of recommended)[z]		Cardy NO_3-N Concentration Corresponding With Maximum Total Yield ($mg \cdot kg^{-1}$)[y]					
			Early		Mid-season		Late	
	Idaho	Font.	Idaho	Font.	Idaho	Font.	Idaho	Font.
Mineral								
2002	0	0	290	1091	150	310	220	110
2003	200	135	709	1128	297	801	220	356
2004	107	74	619	1764	167	261	190	294
Organic								
2002	0	0	790	1040	460	560	60	280
2003	0	0	350	600	260	390	170	210
2004	0	0	890	990	170	250	160	220

[z] Calculated from regression equations for each cultivar where significant, and assuming no N rate is desired rate where no effect of N on total yield exists. Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.

[y] Calculated from regression equations where significant, or the corresponding NO_3-N concentration to the rate listed.

carrots had consistently lower critical NO_3-N concentrations than 'Fontana', especially at the first two sampling dates (Table 2.9).

Soil NO_3-N concentrations as determined by the Cardy meter increased with increasing N rate in all three years and on both soil types (Table 2.10). At the late sampling stage on mineral soil in 2004, the relationship between N rate and soil NO_3-N readings was quadratic, increasing at an increasing rate as N application rate increased. Laboratory NO_3-N readings taken during the mid-season sampling stage (late-season on organic soil in 2003) also increased with increasing N rate in all cases. Soil total N concentrations as determined by the laboratory at the same sampling stages (not tested in 2003) were not influenced by N application rate (Table 2.10).

Soil total N concentrations as determined by the laboratory were not correlated with Cardy meter soil NO_3-N concentrations in any of the three years (Table 2.11). Cardy meter soil NO_3-N concentrations were highly correlated with laboratory soil NO_3-N results on both soil types in all three years and in all three sampling stages in 2002 (Table 2.11). However, the conversion factors between laboratory and Cardy meter results, which could be used to equate Cardy meter readings to laboratory results, were highly variable, especially on organic soil. The conversion factor on mineral soil ranged from 0.80 to 1.03. The 2004 conversion factor was lower, but the 2004 samples were assessed using a different laboratory procedure and cannot be compared. On organic soil the conversion factors ranged from 3.15 to 6.39, and the factor was 0.32 when a different laboratory tested the samples in 2004 (Table 2.11). A large portion of this variability on organic soil could be attributed to the variability in results as determined by the laboratory described earlier. Critical soil NO_3-N concentrations, established based on the

Table 2.10. Effect of nitrogen (N) over three consecutive years on nitrate-N (NO_3-N) concentration of mineral and organic soil (30 cm depth) early (55-66 days after seeding (DAS)), mid-season (87-96 DAS), and late (116-126 DAS) grown to carrots from 2002 to 2004.

N rate (% of recommended)[z]		Mineral Soil					Organic Soil				
		Cardy NO_3-N ($mg \cdot kg^{-1}$)			Laboratory Results[y]		Cardy NO_3-N ($mg \cdot kg^{-1}$)			Laboratory Results[y]	
		Early	Mid-Season	Late	NO_3-N $mg \cdot kg^{-1}$	Total N (%)	Early	Mid-Season	Late	NO_3-N $mg \cdot kg^{-1}$	Total N (%)
2002	0	18.8	14.3	12.3	15.0	0.08	44.5	9.5	28.5	83.6	2.36[x]
	50	28.5	23.0	35.3	22.4	0.08	68.0	17.0	30.0	100.7	2.39
	100	54.8	52.5	31.8	52.2	0.09	75.0	35.0	42.0	178.7	2.38
	150	90.5	81.0	60.8	79.4	0.08	97.0	35.0	53.5	124.3	2.42
	200	115.8	96.5	90.0	89.0	0.09	131.5	59.5	63.0	246.7	2.39
Significance	L	***	***	***	***	NS	***	***	**	**	NS
	Q	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	0.68	0.76	0.73	0.75	--	0.63	0.69	0.36	0.56	--
2003	0	10.5[x]	8.8	7.3[x]	1.2	--	29.0	28.0	16.0[x]	76.8	--
	50	20.3	12.3	9.5	5.9	--	63.5	38.5	20.5	84.6	--
	100	26.5	15.3	18.0	12.6	--	87.5	63.0	38.0	214.7	--
	150	23.0	52.3	25.3	78.5	--	76.5	98.0	60.5	264.0	--
	200	44.8	64.3	35.8	100.2	--	116.0	96.0	68.7	346.3	--
Significance	L	**	***	***	***	--	***	***	***	**	--
	Q	NS	NS	NS	NS	--	NS	NS	NS	NS	--
	R^2	0.43	0.59	0.61	0.62	--	0.49	0.52	0.64	0.56	--
2004	0	11.0[x,w]	12.8[x]	12.5[x]	9.0	0.13[x]	29.0[x,v]	18.5[x]	19.5[x]	7.3[x]	1.81[x]
	50	23.0	18.0	14.5	9.0	0.12	45.5	21.5	25.0	7.3	1.79
	100	42.3	28.5	16.8	13.3	0.12	65.0	59.5	31.0	11.8	1.87
	150	41.3	44.7	36.0	40.8	0.13	64.5	57.5	41.5	23.3	1.85
	200	66.7	79.8	55.3	45.5	0.14	88.0	57.3	64.7	21.0	1.90
Significance	L	***	***	***	***	NS	***	*	***	**	NS
	Q	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
	R^2	0.75	0.77	0.75	0.60	--	0.68	0.31	0.54	0.33	--

[z] Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.
[y] Samples taken during the second sampling date (third for organic soil in 2003) and sent to a laboratory for total N (all three years) and NO_3-N (2002 and 2004 only) analysis.
[x] One outlier removed for calculation of means and statistical analysis.
[w] Two outliers removed for calculation of means and statistical analysis.
[v] Data does not follow a normal distribution.
[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table 2.11. Linear correlation statistics and conversion factors for the comparison between Cardy soil nitrate-N (NO_3-N) readings and laboratory soil total N and NO_3-N results for organic and mineral soils.

Year	Linear Correlation Statistics					
	Total N			NO_3-N		
	P	r	Conversion[z]	P	r	Conversion
Organic						
2002-early	0.5248	-0.18	0.0323 (0.00329)[y]	0.0001	0.83	3.905 (0.2145)
2002-mid	0.6335	-0.13	0.1415 (0.0365)	<.0001	0.88	6.385 (0.7711)
2002-late	0.1379	-0.40	0.0690 (0.0108)	<.0001	0.85	3.147 (0.2637)
2003	--	--	--	<.0001	0.96	4.869 (0.3194)
2004	0.5926	0.13	0.0485 (0.00348)	<.0001	0.91	0.323 (0.0362)
Mineral						
2002-early	0.9656	-0.01	0.00249 (0.000479)	<.0001	0.86	0.801 (0.0623)
2002-mid	0.9149	0.03	0.00255 (0.000472)	<.0001	0.97	0.950 (0.0339)
2002-late	0.8420	-0.06	0.00288 (0.000490)	<.0001	0.92	0.884 (0.0477)
2003	--	--	--	<.0001	0.92	1.0349 (0.1991)
2004	0.2394	0.28	0.00517 (0.000981)	<.0001	0.88	0.609 (0.0433)

[z] Equation: Cardy sap NO_3-N x conversion factor = Laboratory total N or NO_3-N concentrations.
[y] Reported as mean (standard error).

NO_3-N concentrations corresponding with the maximum total yield, were highly variable (Table 2.12).

Soil N concentrations in the top 30 cm prior to the start of the 2002 season were 24.4 $mg \cdot kg^{-1}$ NH_4^+, 89.1 $mg \cdot kg^{-1}$ NO_3^-, and 2.4% total N for the organic soil plot, and 2.4 $mg \cdot kg^{-1}$ NH_4^+, 2.3 $mg \cdot kg^{-1}$ NO_3^-, and 0.09% for the mineral soil plot. Soil samples were only collected from the recommended rate treatment on both soil types at harvest in 2002, and no trends can be identified. Post-harvest concentrations of total N in organic soil in the top 30 cm in 2003 increased with increasing N rate (Table 2.13). In all other cases for both soil types, soil N concentrations were unaffected by N application rate (Table 2.13). Soil total N concentrations in 2004 in mineral soil decreased below 30 cm, but were steady between the 30-60 cm and the 60-90 cm depths (Table 2.13). In organic soil in 2004, soil total N concentrations increased with increasing depth both pre-seeding and post-harvest at all three N rates tested. Soil total N concentrations were much higher in organic soil than in mineral soil (Table 2.13).

Soil NO_3-N concentrations generally increased with increasing N rate both pre-seeding and post-harvest in both soil types (Table 2.14). The exception was at the 60-90 cm depth, where no effect of N rate was observed. However, soil NO_3-N concentrations were numerically much greater at all three depths at the high rate of N in all cases in mineral soil. Prior to the 2004 growing season in mineral soil there was a significant pool of NO_3-N below the 30 cm depth. Except for this case, NO_3-N concentrations of the soil tended to decrease with increasing depth in the soil profile (Table 2.14).

Ammonium-N concentrations decreased slightly with increasing N rate pre-seeding in mineral soil in 2003 and the top 30 cm in organic soil in 2004, and post-

Table 2.12. Soil nitrate-N (NO_3-N) concentrations in the top 30 cm for each soil type that correspond with the N rate producing the maximum yield of carrots from 2002 to 2004.

Soil Type	N rate with maximum total yield (% of recommended)[z]	Cardy NO_3-N Concentration Corresponding With Maximum Total Yield ($mg \cdot kg^{-1}$)[y]			
		Preplant (lab)	Early	Mid-season	Late
Mineral					
2002	0	--	10.5	9.0	9.8
2003	200	2.3	40.2	60.8	33.9
2004	91	6.3	34.8	34.2	17.7
Organic					
2002	0	--	42.6	7.6	24.9
2003	0	12.5	37.1	25.6	11.6
2004	0	9.3	31.1	19.6	15.4

[z] Calculated from regression equations for each cultivar where significant, and assuming no N rate is desired rate where no effect of N on total yield exists. Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.

[y] Calculated from regression equations where significant, or the corresponding NO_3-N concentration to the rate listed.

Table 2.13. Effect of nitrogen (N) application rate over three years on total N concentration (%) at various depths of mineral and organic soils grown to carrots from 2002 to 2004.

N rate[z]	2002	2003		2004					
	Post-harvest	Pre-seeding	Post-harvest	Pre-seeding			Post-harvest		
	Top 30 cm	Top 30 cm	Top 30 cm	Top 30 cm	30-60 cm depth	60-90 cm depth	Top 30 cm	30-60 cm depth	60-90 cm depth
Mineral									
0	--	0.12	0.07	0.12	0.06	0.03	0.13	0.06	0.09
50	--	0.08	--	0.12	--	--	0.12	--	--
100	0.08	0.09	0.06	0.11	0.04	0.06	0.13	0.06	0.08
150	--	0.08	--	0.12	--	--	0.14	--	--
200	--	0.08	0.09	0.11	0.05	0.04	0.15	0.07	0.04
Sign. L	--	NS	NS	NS	NS	NS	NS	NS	NS
Q	--	NS	NS	NS	NS	NS	NS	NS	NS
R^2	--	--	--	--	--	--	--	--	--
Organic									
0		1.76	1.88	1.68[y]	1.74	2.55	1.83[y]	1.90	2.13
50		1.86	--	1.73	--	--	1.77	--	--
100	2.35	1.82	1.98	1.64	1.99	2.22	1.78	2.48	2.91
150		1.75	--	1.59	--	--	1.82	--	--
200		1.90	2.13	1.65	1.90	2.61	1.74	1.82	2.72
Sign. L		NS	*	NS	NS	NS	NS	NS	NS
Q		NS	NS	NS	NS	NS	NS	NS	NS
R^2		--	0.58	--	--	--	--	--	--

[z] Percent of Recommended. Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.
[y] One outlier removed for mean calculation and statistical analysis.
NS,*,**,*** Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table 2.14. Effect of nitrogen (N) application rate over three years on nitrate-N (NO_3-N) concentration ($mg \cdot kg^{-1}$) at various depths of mineral and organic soils grown to carrots from 2002 to 2004.

N rate[z]		2002	2003		2004					
		Post-harvest	Pre-seeding	Post-harvest	Pre-seeding			Post-Harvest		
		Top 30 cm	Top 30 cm	Top 30 cm	Top 30 cm	30-60 cm depth	60-90 cm depth	Top 30 cm	30-60 cm depth	60-90 cm depth
Mineral										
0		--	3.5	3.7	7.0	2.0	2.0	3.8	1.0	1.3
50		--	5.5	--	5.5	--	--	6.3	--	--
100		25.9	7.5	8.0	6.3	2.0	1.3	10.8	1.7	1.3
150		--	14.0	--	5.8	--	--	54.3	--	--
200		--	17.8	71.0	8.7	11.7	13.7	56.0	6.3	4.7
Sign.	L	--	***	NS	NS	*	NS	***	***	NS
	Q	--	NS	NS	NS	NS	NS	NS	*	NS
	R^2	--	0.53	--	--	0.56	--	0.63	0.90	--
Organic										
0		--	13.5	12.0	9.3	6.7	7.0	5.0[y]	7.0	2.7
50		--	13.8	--	10.0	--	--	4.5	--	--
100		76.8	15.3	21.7	14.5	13.0	8.7	8.0	4.0	3.3
150		--	18.3	--	9.3	--	--	12.5	--	--
200		--	20.8	38.3	13.0	6.3	6.3	16.3	9.0	4.0
Sign.	L	--	*	*	NS	NS	NS	***	NS	NS
	Q	--	NS	NS	NS	*	NS	*	NS	NS
	R^2	--	0.22	0.56	--	0.61	--	0.84	--	--

[z] Percent of recommended. Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.
[y] One outlier removed for mean calculation and statistical analysis.
NS,*,**,*** Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

harvest in the top 30 cm in organic soil in 2004 (Table 2.15). In all other cases there were no effects of N application rate on soil NH_4-N concentrations (Table 2.15). In mineral soil, NH_4-N concentrations tended to decrease below the 30 cm depth, but the opposite was true in organic soil (Table 2.15).

Within the three N application rates examined, there were no relationships between preplant available N in the top 30, 60, or 90 cm of the soil and total yield on organic soil (data not shown). On mineral soil, there were significant quadratic relationships between preplant available N in the top 30 (R^2=0.76) and top 60 cm (R^2=0.80) of the soil and total yield, but no relationship between yield and preplant available N in the top 90 cm of the soil. The preplant available N level in the top 60 cm producing the highest total yield was calculated to be 166 $kg \cdot ha^{-1}$ N for mineral soil. By comparison, there was no relationship between N application rate and total yield for the three rates and three replications used in this analysis.

Over the three years different sequences of the recommended rate, late sidedresses, and no N application were tested to determine if yield could be improved in later years by proper sequence of N application within and among the years and these results are listed in Appendix 1. Preplant N had more effect on yield than sidedress N in most cases, but sidedress N did increase yield over the no N control treatment in some cases.

Field Observations: 'Fontana' carrots were observed to have weaker and smaller canopies over the second half of the growing season than 'Idaho' carrots. Canopy closure occurred near the end of July on organic soil, but only occurred at the high N rates on

Table 2.15. Effect of nitrogen (N) application rate over three years on ammonium-N concentration ($mg \cdot kg^{-1}$) at various depths of mineral and organic soils grown to carrots from 2002 to 2004.

N rate[z]	2002	2003		2004					
	Post-harvest	Pre-seeding	Post-harvest	Pre-seeding			Post-Harvest		
	Top 30 cm	Top 30 cm	Top 30 cm	Top 30 cm	30-60 cm depth	60-90 cm depth	Top 30 cm	30-60 cm depth	60-90 cm depth
Mineral									
0	--	3.8	2.3	2.0	1.0	1.0	1.8	1.7	1.7
50	--	3.3	--	2.0	--	--	2.3	--	--
100	1.9	3.0	1.7	2.3	1.7	1.3	2.0	1.0	1.7
150	--	2.8	--	2.0	--	--	2.0	--	--
200	--	2.5	2.0	2.3	1.7	1.3	2.5	2.3	1.3
Sign. L	--	*	NS	NS	NS	NS	NS	NS	NS
Q	--	NS	NS	NS	NS	NS	NS	NS	NS
R^2	--	0.24	--	--	--	--	--	--	--
Organic									
0	--	2.0	2.0	4.3	5.0	5.0	4.3	5.0	4.0
50	--	2.3	--	3.8	--	--	3.8	--	--
100	13.2	2.0	2.3	3.3	5.3	5.0	3.3	5.0	5.0
150	--	2.0	--	2.5	--	--	3.5	--	--
200	--	1.8	2.0	3.0	5.0	5.3	3.3	4.0	5.0
Sign. L	--	NS	NS	*	NS	NS	*	NS	NS
Q	--	NS	NS	NS	NS	NS	NS	NS	NS
R^2	--	--	--	0.23	--	--	0.23	--	--

[z] Percent of recommended. Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.
[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

mineral soil. Aster yellows was observed to increase each year of the experiment on mineral soil, and became excessive in 2004. The largest amount of aster yellows appeared to occur in the areas where seedling damage due to high N occurred. Wilting symptoms due to low rainfall were visible in both 2002 and 2003 on mineral soil, but only occurred for a two to four week period in small areas of the plot. Two 1 m deep holes dug between the carrot rows in October on both mineral and organic soil in 2002 indicated fibrous roots at 95 cm below the surface on both soil types. The top of the water table occurred near 90 cm below the surface for both soils and deeper observations were not possible.

2.3.2 Foliar Nitrogen

Both cultivars had similar responses to treatment, as shown by a lack of treatment/cultivar interactions, and combined results are reported. On mineral soil in 2002 and 2004, there was no effect of foliar N application or N timing on total yield (Table 2.16). In 2003 on mineral soil, total yield increased with an increase in the amount of N applied, regardless of the time of application. Foliar N with surfactant produced a higher total yield than the no N treatment (Table 2.16). There were no effects of treatment on total yield on organic soil in 2002 and 2003 (Table 2.16). In 2004, there was a higher total yield in carrots that received foliar sprays with surfactant than carrots that received no N (Table 2.16). The carrots receiving 50% of recommended preplant plus foliar sprays with surfactant had the highest total yield, and significantly higher than all treatments except the no preplant N with foliar sprays with surfactant treatment (Table 2.16).

Table 2.16. Effect of foliar nitrogen (N) and N timing on total yield of carrots grown on mineral and muck soil in 2002, 2003, and 2004 in separate locations each year (average of two cultivars).

Treatment (% of Recommended)[z]		Total Yield ($t \cdot ha^{-1}$)					
Pre-plant N	Addi-tional[y]	Mineral Soil			Organic Soil		
		2002	2003	2004	2002	2003	2004
0	0	41.6 a[x]	38.1 a	47.4 a	94.4 a	100.1 a	81.1 a
0	Foliar	44.8 a	43.7 b	44.2 a	91.6 a	96.8 a	95.0 cd
0	Foliar-S	--	39.5 ab	47.0 a	--	96.9 a	87.1 a-c
50	Foliar	45.3 a	54.5 c	45.5 a	92.8 a	99.5 a	102.4 d
100	Foliar	41.6 a	63.5 de	46.4 a	93.8 a	97.3 a	92.0 bc
50	50	42.5 a	59.9 d	43.7 a	96.2 a	100.4 a	85.9 ab
0	50	--	--	--	--	--	87.6 a-c
0	100	46.1 a	60.0 d	44.8 a	91.0 a	--	86.7 a-c
0	200	--	67.8 e	43.6 a	--	--	--

[z] Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.

[y] Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea (with AGRAL 90 surfactant added in 2003 and 2004) beginning when canopy is 75% closed; Foliar-S = same as Foliar treatment without surfactant.

[x] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Marketable yield, weight per root, and the distribution among the size and quality grades paralleled the effect of foliar N on total yield and were mainly influenced by preplant N rate (Appendix 2). Stand at harvest was unaffected by foliar N or preplant N application rate (Appendix 2).

Sap NO_3-N concentrations were unaffected by foliar treatment on both soil types in all three years (Table 2.17). The differences that did exist can be mostly explained by the preplant N rate. There is no evidence to suggest that foliar sprays with or without surfactant increase the NO_3-N concentration of petiole sap. On organic soil in 2004 early in the season, carrots in the foliar spray with surfactant treatment had a lower sap NO_3-N concentration than carrots given no preplant or foliar N (Table 2.17).

Soil N concentrations in the top 30 cm prior to seeding for organic soil were determined to be 1.3 and 1.8% total N, 14.5 and 18.3 $mg \cdot kg^{-1}$ NO_3-N, and 3.3 and 3.5 $mg \cdot kg^{-1}$ NH_4-N for 2003 and 2004, respectively. For mineral soil, soil N concentrations in the top 30 cm prior to seeding were determined to be 0.2 and 0.3% total N, 8.8 and 20.5 $mg \cdot kg^{-1}$ NO_3-N, and 3.5 and 2.3 $mg \cdot kg^{-1}$ NH_4-N for 2003 and 2004, respectively.

2.3.3 Root Depth and Nitrogen Uptake

Increasing the N concentration of the fertilizing solution in the greenhouse increased top and storage root dry weight of 'Idaho' carrots up to the recommended rate (for a 25 or 50% Hoagland solution), but increasing the N concentration beyond the recommended rate decreased top and storage root weight (Table 2.18). The fibrous root dry weight was unaffected by N rate for 'Idaho' carrots. 'Fontana' carrot top and root dry weights were not affected by N rate. Fibrous root depth was unaffected by N rate, and the fibrous roots were down to the maximum150 cm depth in nearly half of the pots

Table 2.17. Effect of foliar nitrogen (N) on sap nitrate-N (NO_3-N) concentrations of carrots grown on mineral soil in 2002, 2003, and 2004 in separate locations each year.

Treatment[z]	Sap NO_3-N Concentrations ($mg \cdot kg^{-1}$)					
	Mineral			Organic		
	Early	Mid-season	Late	Early	Mid-season	Late
2002						
0	364 a[y]	77 a	182 a	1413 a	623 a	214 a
0 + Foliar	373 a	79 a	152 a	1248 a	648 a	106 a
50 + Foliar	579 b	118 ab	223 a	1319 a	450 a	158 a
100 + Foliar	715 b	140 b	216 a	1316 a	658 a	223 a
2003						
0	302 a	200 a	203 a	1668 a	748 a	679 a
0 + Foliar	276 a	216 a	203 a	1634 a	645 a	592 a
50 + Foliar	540 b	197 a	196 a	1481 a	520 a	661 a
100 + Foliar	507 b	224 a	191 a	1711 a	630 a	552 a
2004						
0	1101 a	566 a	547 a	1124 b	393 a	314 a
0 + Foliar	1130 a	512 a	445 a	812 a	260 a	243 a
50 + Foliar	1251 a	693 a	583 a	1066 ab	422 a	291 a
100 + Foliar	1228 a	714 a	616 a	1256 b	388 a	269 a

[z] Numbers indicate percent of recommended N application rate: recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress. Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea once rows were 75% covered with Agral 90 surfactant added in 2003 and 2004 only.

[y] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table 2.18. Effect of nitrogen (N) application rate and on dry weight and fibrous root depth of two carrot cultivars grown in silica sand in the greenhouse in 150-cm deep PVC pipes.

N Rate[z]/ Cultivar		Dry Weight (g)			Root Depth	Ratio				
						Top Weight to			Storage Root Weight to	
		Top	Storage Root	Fibrous Root		Storage Root Weight	Fibrous Root Weight	Total Root Weight	Fibrous Root Weight	Root Depth
Idaho										
50		0.72[y]	4.09[y]	1.17	102.1	0.17	0.77	0.12	4.58	0.041[y]
100		2.04	9.33	1.77	135.1	0.22	1.29	0.18	6.77	0.068
200		1.08	4.65	1.66	117.9	0.27	1.19	0.18	5.85	0.042
Sign.	L	NS	NS	NS	NS	*	NS	NS	NS	NS
	Q	**	**	NS	NS	NS	NS	NS	NS	*
	R^2	0.37	0.37	--	--	0.20	--	--	--	0.26
Fontana										
50		0.89	5.59[y]	1.68[y]	111.3	0.17	0.82	0.12	5.51	0.055[y]
100		1.04	5.12	1.46	92.3	0.22	1.10	0.16	6.22	0.077
150		0.91	4.28	0.93	102.9	0.18	1.05	0.14	6.68	0.056
Sign.	L	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--	--	--	--

[z] Numbers indicate percent of N required for a 50% Hoagland solution.
[y] One outlier removed for calculation of means and statistical analysis.

examined (Table 2.18). The top weight to storage root weight ratio increased with increasing N rate for 'Idaho' carrots. The storage root weight to fibrous root depth ratio increased with increasing N rate up to a maximum at the recommended N rate, and then decreased above the recommended rate for 'Idaho' carrots (Table 2.18). In all other cases there were no effects of N rate on top to root, or storage root to fibrous root ratios. There were no differences between the cultivars in any of the parameters tested (Appendix 2).

The total weight of fibrous roots was lowest at 50% of the full N rate for 'Fontana' carrots (Figure 2.2), but tended to decrease with increasing N rate for 'Idaho' carrots (Figure 2.3). In two cases, an outlier was removed from the data set that exhibited much more fibrous roots in the top 30 cm, and these outliers were due to damage to the taproot that resulted in proliferation of the lateral roots. Between 35.2 and 61.4% of the fibrous roots were found below 30 cm depth, and between 6.3 and 13.1% of the fibrous roots were found below 90 cm depth (Figures 2.2 and 2.3). Both cultivars showed similar distributions of fibrous roots within the five sections of the soil profile (Figure 2.4). 'Idaho' carrots produced more roots below 90 cm than 'Fontana' carrots (Figure 2.4).

2.3.4 Nitrogen Uptake of Cultivars

There were no differences between the two cultivars in the dry weight of new or old leaves or the dry weight of the storage root in the ^{15}N pot experiment conducted outside during the summer of 2003 in soilless mix. 'Fontana' carrots recovered more N from ^{15}N-enriched fertilizer in the new leaves at the early September application date than 'Idaho' carrots (Table 2.19). In all other cases there were no differences between the two cultivars in the recovery of N from fertilizer. Three weeks after 10%-enriched ^{15}N fertilizer application in early August, 67% of the N in the new leaves, 38% of the N in the

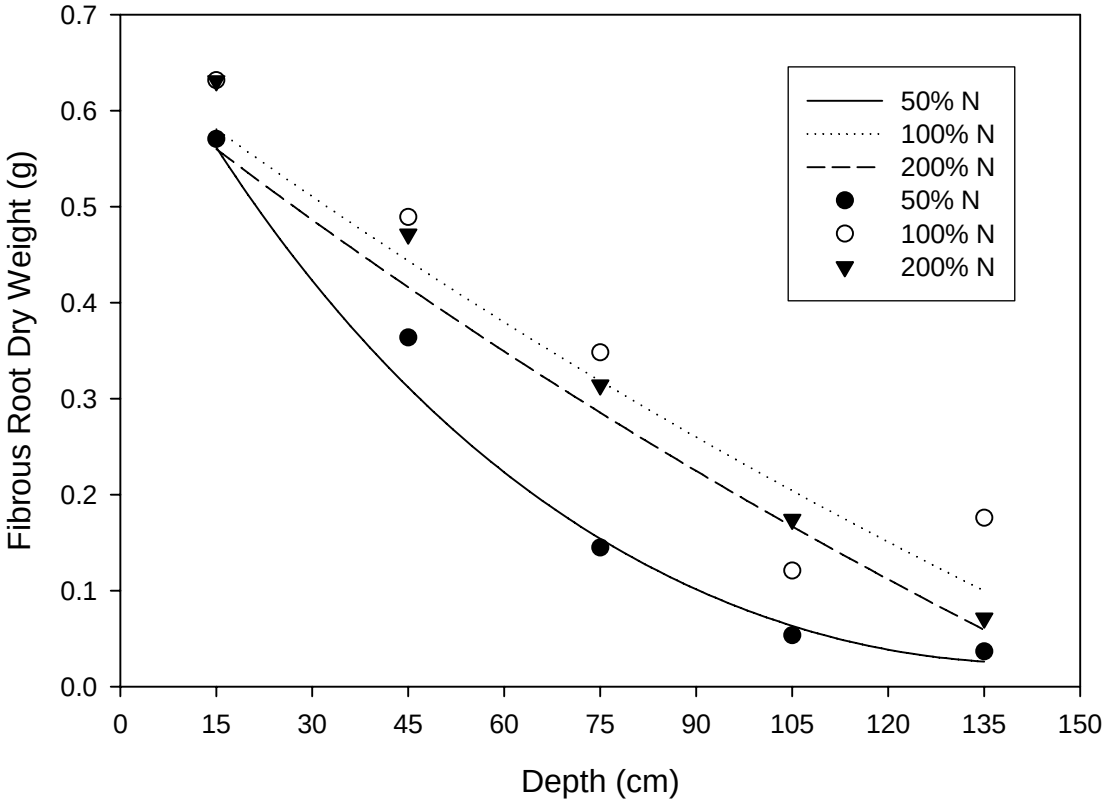

Figure 2.2. Distribution of fibrous root dry weight in the soil profile for 'Fontana' carrots grown in 10 cm diameter PVC pipes in 98% pure silica sand as affected by nitrogen (N) application rate. Observations represent dry weight of the roots in each 30 cm section below the top of the soil column. Equations: 50N (outlier 2.261 removed) R^2=0.39 ln(weight)=[0.4896 – 0.0035772(depth)]-1.0; 100N (outlier 1.794 removed) R^2=0.25 ln(weight)=[0.4035 – 0.002742(depth)]-1.0; 200N R^2=0.58 ln(weight)=[0.5430 – 0.008445(depth) + 0.00003410(depth)^2]-1.0.

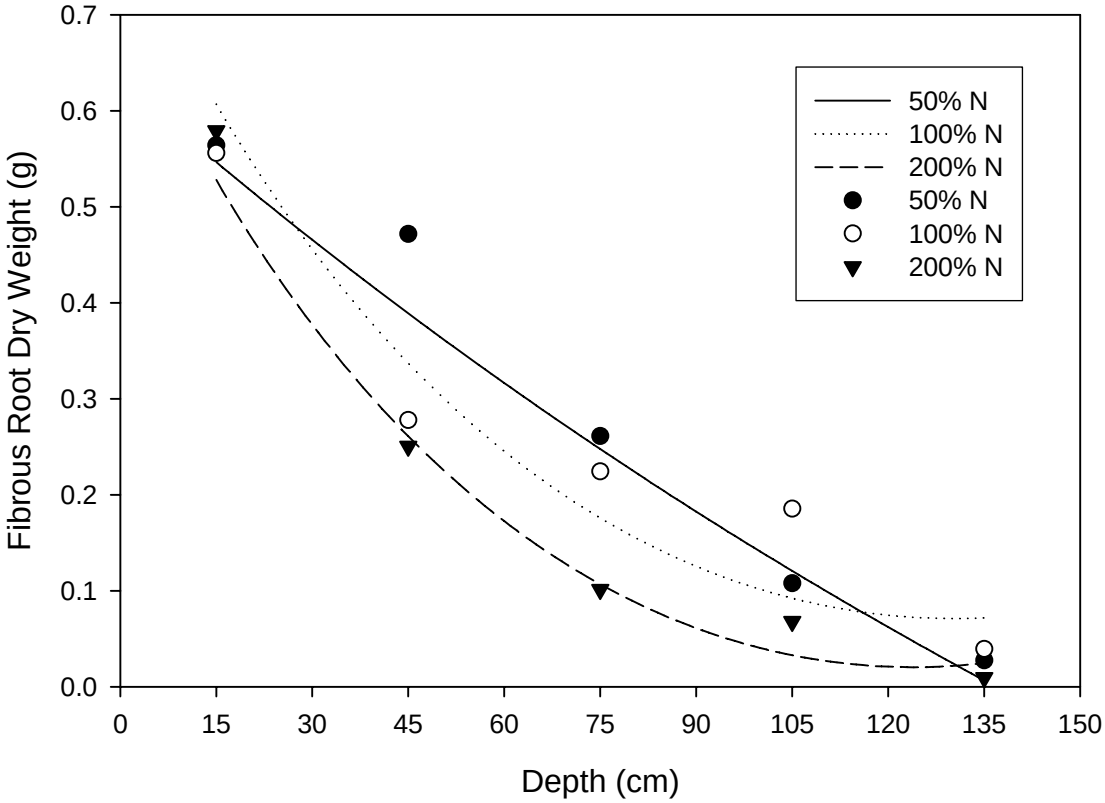

Figure 2.3. Distribution of fibrous root dry weight in the soil profile for 'Idaho' carrots grown in 10 cm diameter PVC pipes in 98% pure silica sand as affected by nitrogen (N) application rate. Observations represent dry weight of the roots in each 30 cm section below the top of the soil column. Equations: 50N R^2=0.61 ln(weight)=[0.5503 – 0.007352(depth) + 0.00002568(depth)^2] -1.0; 100N R^2=0.33 ln(weight)=[0.5031 – 0.003023(depth)]-1.0; 200N R^2=0.29 ln(weight)=[0.4930 – 0.002602(depth)]-1.0.

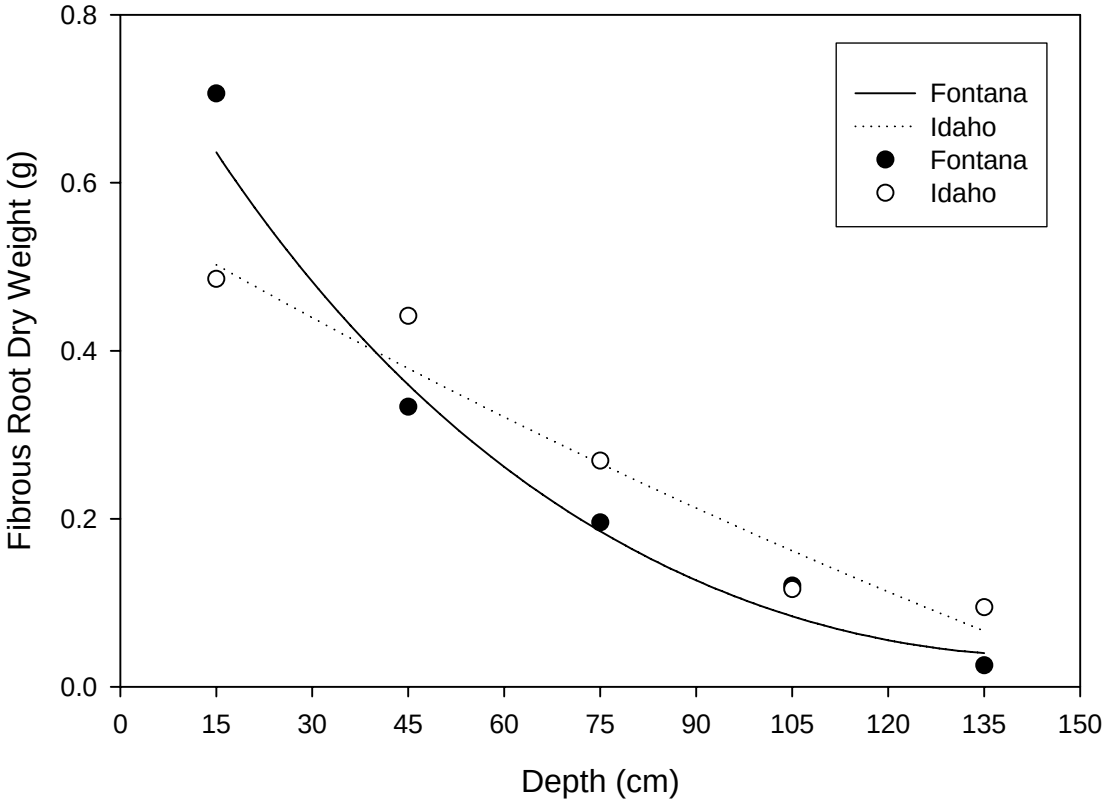

Figure 2.4. Distribution of fibrous root dry weight in the soil profile for two carrot cultivars grown in 10 cm diameter PVC pipes in 98% pure silica sand. Data from three N application rates (50, 100, and 200% of complete Hoagland solution) were pooled. Equations: Font R^2=0.57 ln(weight)=[0.6029 – 0.007768(depth) + 0.00002662(depth)^2] -1.0; Idaho (outlier 1.363 removed) R^2=0.58 ln(weight)=[0.4499 – 0.002857(depth)] -1.0.

Table 2.19. Dry weight of new and old leaves and storage root and recovery of nitrogen (N) three weeks after fertilization at two dates (separate pots each date) with 500 ml of 10% ^{15}N enriched potassium nitrate (2.42 $g \cdot L^{-1}$) of two carrot cultivars grown outside during the summer in 15 cm diameter pots filled with ASB soilless potting mix.

Cultivar	Percent of total N recovered from ^{15}N fertilizer (%)						Dry Weight (g)					
	New Leaves		Old Leaves		Storage Root		New Leaves		Old Leaves		Storage Root	
	12 Aug.	4 Sept.	12 Aug.	4 Sept.	12 Aug.	4 Sept.	12 Aug.	4 Sept.	12 Aug.	4 Sept.	12 Aug.	4 Sept.
Idaho	67.3 a[z]	50.2 a	37.5 a	18.6 a	53.8 a	37.8 a	5.18 a	6.18 a	4.08 a	4.34 a	14.8 a	24.1 a
Fontana	66.1 a	55.0 b	39.4 a	23.9 a	54.0 a	43.6 a	6.47 a	5.67 a	4.64 a	4.56 a	16.4 a	24.9 a

[z] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

old leaves, and 54% of the N in the storage roots came from ^{15}N-enriched fertilizer (Table 2.19). In separate pots, three weeks after ^{15}N enriched fertilizer application in early September, 53% of the N in the new leaves, 21% of the N in the old leaves, and 41% of the N in the storage root came from ^{15}N-enriched fertilizer (Table 2.19).

2.3.5 Distribution of Nitrogen Uptake

Carrots grown in soilless media in 150 cm PVC pipes recovered no ^{15}N in pipes in which the fibrous roots did not reach the injection site. This shows that there was minimal rise of the ^{15}N up the soil column due to capillary action. Carrots recovered more N from ^{15}N-enriched fertilizer when fertilizer was injected at 30 cm depth than at the lower depths (Table 2.20). The number of roots crossing the injection site was also much higher at the 30 cm depth (Table 2.20). When factoring in the amount of roots available to take up ^{15}N fertilizer, there were no differences in the amount of ^{15}N recovered per root available to take it up. Consequently, total N recovery from each depth was proportional to the number of roots present at that depth. There were no statistical differences in the recovery of N between the cultivars (Appendix 2). Total recovery of ^{15}N-enriched fertilizer was very low, suggesting that there was insufficient time allowed for the roots to take up the ^{15}N fertilizer. Both cultivars showed a similar logarithmic decrease in number of roots with increased depth in the soil profile (Figure 2.5). In contrast to the sand experiments described above, only 11.3 to 24.8% of the roots were below 30 cm depth and less than 1% of the roots were below the 90 cm depth (Figure 2.5).

Additional Observations: Carrots were injected with safranin O dye in an attempt to develop a procedure for testing rooting depth and distribution in the field. While only one

Table 2.20. Recovery of total nitrogen (N) and ^{15}N in carrot tops and roots following injection of 10% ^{15}N enriched potassium nitrate fertilizer injected at three different depths in 150 cm deep PVC pipes as compared to the number of roots crossing the injection site.

Injection Site	Number of roots crossing injection site	Total N recovered (μg)			^{15}N recovered per root crossing injection site (μg)		
		New Leaves	Old Leaves	Roots	New Leaves	Old Leaves	Roots
Upper (30 cm)	23.6 b[z]	101.4 b	59.6 b	189.8 b	3.89 a	2.41 a	7.15 a
Lower (80+130 cm)	5.6 a	11.1 a	6.6 a	16.2 a	4.42 a	2.97 a	7.49 a

[z] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

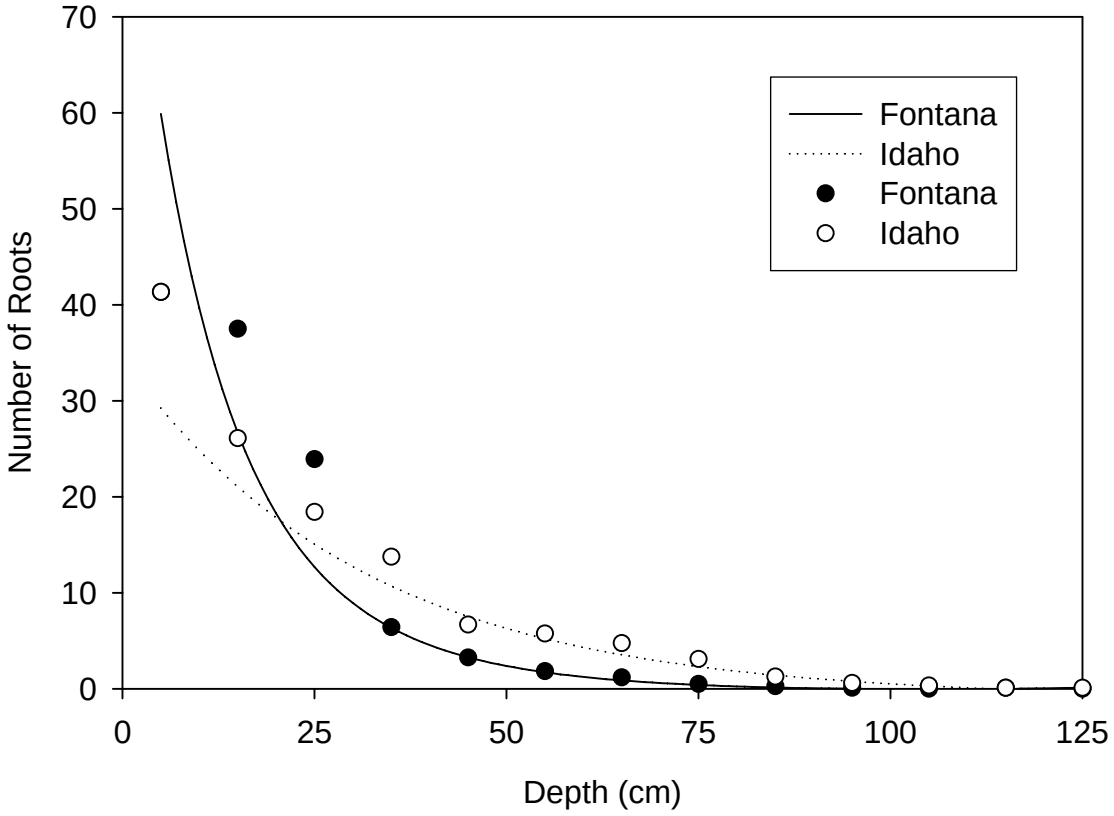

Figure 2.4. Fibrous root distribution of carrots grown in soilless medium in the greenhouse in 150-cm deep PVC pipes as affected by cultivar. Equations: Font $\ln(\text{weight})=[4.5338 - 0.08702(\text{depth}) + 0.0004130(\text{depth})^2]-1.0$; Idaho $\ln(\text{weight})=[3.5679 - 0.03168(\text{depth})]-1.0$.

carrot out of 40 assessed took up the dye, observations of that storage root reveal that dye taken up by the taproot travelled directly through the vascular tissue to the leaves, without any transfer into the parenchyma tissues surrounding the pith (Figure 2.6).

2.4 Discussion

2.4.1. Effects of N Application Rate on Carrot Yield and Quality

As in previous research in temperate regions showing little response of carrot to applied N (Hamilton and Bernier, 1975; Burdine and Hall, 1976; Venter, 1979; Wiebe, 1987; Evers, 1988; Rühlmann and Geyer, 1993; Warncke, 1996; Sanderson and Ivany, 1997; Gutezeit, 1999; Couper, 2001; Westerveld, 2002), carrot yield did not respond to N application rate or preplant available N on organic soil. It is clear that sufficient N was released by mineralization of organic matter over the growing season or there was sufficient residual N to supply the N requirements of the crop for optimal storage root growth, and no negative consequences of either high or low N application rates on the storage root could be identified. The results are in contrast to reports from tropical and sub-tropical regions, showing a large yield response to applied N (Arora and Mathur, 1972; Burdine and Hall, 1976; Hipp, 1978; Hochmuth et al., 1999; Kumazawa, 2002). It is likely that the differences between temperate and tropical regions are mainly due to less rainfall, resulting in less leaching (Hochmuth et al., 1999), and the ability of carrots to take up N from deep in the soil profile in temperate regions because of the slower leaching rates. However, potential effects of N on the ability to harvest the crop and on leaf blight severity were not examined in this chapter and are discussed in Chapter 4.

On mineral soil, there was also no response to applied N in the first year on the site. The mineral soil site had remained fallow with extensive weed cover for several

Figure 2.5. Cross-section of a white carrot storage root grown in soilless mix in a 15-cm diameter pot two weeks after injection of safranin O dye into the soilless mix.

years prior to the 2002 season, which could have caused an accumulation of organic matter with a low carbon:N (C:N) ratio by the 2002 season. This would have resulted in a large release of N by mineralization, and could explain the lack of N effect on yield in 2002. Since no yield response to applied N occurred in the first year, carrots may not require N application when grown within a crop rotation, but the response to applied N would depend on residual N from the preceding crop. Previous research reveals that carrot yield depends on the preceding crop, with onions, potatoes, chicory, and peppers being the most beneficial for high carrot yields (Markovic et al., 2002). The reasons for these effects were not examined, but it is likely that nutrition plays a significant role. Likely due to the low organic matter content of the soil on this site, lower mineralization rates over time, and removal of residual N from the soil in 2002, both sections of the experiment in 2003 revealed an increase in yield and weight per root with increasing N rate up to the maximum rate tested. The yield response to N rate in the alternating fertilizer section suggests that a significant amount of N that was unused in 2002 was still available to the crop by 2003. It also shows that residual N can explain more than half of the yield response that occurred in the annual fertilizer section in 2003. This is illustrated by the fact that, using the regression equations, yield increased from 39.8 $t \cdot ha^{-1}$ to 58.1 $t \cdot ha^{-1}$ (18.3 $t \cdot ha^{-1}$ increase) by increasing N rate from 0 to 200% of the recommended N application rate in the annual fertilizer section, and increased from 36.1 $t \cdot ha^{-1}$ to 47.9 $t \cdot ha^{-1}$ (11.8 $t \cdot ha^{-1}$ increase) over the same N rates applied in 2002 in the alternating fertilizer section. Although deep soil samples were not collected in 2003, the 2004 soil samples reveal that a large pool of NO_3^- existed below 30 cm depth pre-seeding and it is likely that a similar effect would have occurred in 2003. Since the taproot extends below 38.5

cm depth at 24 DAS (White and Strandberg, 1978), carrots would be able to access deep N early in the season. Given that rainfall was below normal in the first three months of the 2003 growing season, it is possible that the N applied in 2003 remained in the dry top layers of the soil where it would be less accessible to the crop, and the induction of deep rooting due to low soil moisture could have caused roots to take up N in deep layers of the profile. The rooting system is discussed in more detail below. If there was insufficient time for preplant-applied N to leach into the rooting zone, a higher response to soil residual N would be expected and this is likely the cause for the results obtained in 2003. The results also suggest that little N must have leached out of the rooting zone over the winter of 2002/2003, even though the soil at this site was over 90% sand. Rainfall during the late summer and fall of 2002 was well below the 10-year mean. However, rainfall was above normal in the month prior to seeding in 2003. Under similar conditions, leaching losses of N over the winter are variable among sites and among years in New Brunswick, with 10-87% losses in sandy soils (Zebarth et al., 2003), and leaching is minimal when soils are frozen in Ontario (Ryan et al., 2000).

In 2004 on mineral soil, yield reached a maximum below the recommended rate and then declined at higher N rates. This result can be attributed to a major loss of stand in the high N treatments in both sections of the experiment. Research reveals a decrease in carrot stand with increasing N rate of 9-13% in Oregon, but the reason for the effect was not investigated (Hemphill and Jackson, 1982). It is unclear what caused the seedling death shown in 2003 and in 2004, but several possibilities exist. Direct toxicity of N is possible, but it would have had to occur under very specific weather and soil conditions because similar N application rates in other plots and years did not result in the same

stand effect. Soil NO_3-N or NH_4-N concentrations were not excessive prior to fertilizer application in 2004, suggesting that the fertilizer applied in 2004 caused the effects on stand. It is also possible that the high N treatment promoted the development of seedling diseases such as damping-off. Since the effect on stand increased each year of the experiment, it is possible that inoculum of the causal organisms accumulated over the three years, resulting in the major damage in 2004. Visual observation of plants that died later in the season in 2004 showed symptoms of crown rot caused by *Rhizoctonia solani* and heat canker. However, the heat canker cannot provide an explanation for the effects at the seedling stage since most of the missing seedlings did not emerge from the ground, and it is unlikely that N rate could affect the susceptibility of seedlings to heat canker. Heat canker damage may have been increased by the thin stands that existed later in the season in high N treatments. On the other hand, NO_3^- fertilizer increases the growth of *R. solani* in culture, and NH_4^+ fertilizer increases carrot infection by *R. solani* (Ghini et al., 2001). It is not known what the relative proportion of the NO_3^- and NH_4^+ forms were at the time of seedling emergence in the current experiment, but preplant concentrations of both were similar among N application rates. Damping-off of peas and cotton caused by *R. solani* and *Pythium ultimum* are reduced with addition of composted sewage sludge, a result that is negatively correlated with N concentration, but many other nutrient and microbial interactions are possible (Lewis et al., 1992). There is no effect of soil N status on seedling diseases of sorghum including *Alternaria sp.* and *Fusarium sp.* (McLaren, 2004). In the present experiment, crown rot was not noted in 2003, when a smaller but still significant effect of N on stand occurred.

The relationship between preplant available N and total yield in 2004 on mineral soil was strongest for the top 60 cm of soil and stronger than the relationship between preplant applied N and total yield. This suggests that yield is strongly influenced by the N available in the top 60 cm of the soil profile at seeding. The optimum preplant available N rate was 166 $kg \cdot ha^{-1}$. Although this value was only tested for one year, it could be used as an indicator of the N available to the crop. It also suggests that soil sampling up to 60 cm depth is important for determining the N supply from the soil, and for adjusting preplant N rates. The importance of deep soil sampling is probably due to the rapid development of carrot roots, which can reach 38.5 cm depth by 24 DAS (White and Strandberg, 1978). However, these results are based on a carrot crop that was grown on the same site without crop rotation for three years, and may not be representative of a typical carrot field. It is unknown whether a similar relationship between yield and preplant available N would occur on organic soil because there were no yield differences among treatments.

The results on mineral soil in 2003 and 2004 reveal that growing carrots on the same location for consecutive years depletes soil N resulting in a yield response. However, the same result did not occur on organic soil. It is unknown if further growth of carrots on the same organic soil location for more years would result in a yield effect. Further research should examine an organic soil carrot/onion rotation for effects of N on crop yield, since this crop rotation is predominant on the Holland Marsh.

Yield generally decreased over time in both plots despite an increase in rainfall in the latter two years. On mineral soil, the decrease in stand at high N rates in 2004 partially explains the reduction in yield. On organic soil, where no effects on stand

occurred, there are two possible explanations for the reduction in yield. First, pest pressures, including carrot rust fly and aster yellows, increased each year of the study, probably due to the lack of crop rotation. Second, in each year there was a period of below normal rainfall that occurred earlier each year. It is possible that plant development was more affected by dry conditions early in the season, possibly due to a less extensive root system and inability to access deep soil moisture at this time or by affecting the early development of the storage root.

The increase in culls that occurred in some cases at high N rates in 2004 could be attributed to increased aster yellows and forking of carrot roots on mineral soil, and increased forking and splitting of carrot roots on organic soil. On mineral soil, these effects are probably a direct result of partial damage that occurred in the seedling stage due to the same problem that decreased stand, and the increase in aster yellows could be due to preferential feeding by the vector, the aster leafhopper (*Macrosteles quadrilineatus* (Forbes)). A relationship between N fertilization and leafhoppers has been noted previously. Oviposition of the potato leafhopper (*Empoasca fabae*) is increased with increased N fertilizer level in maple selections (Bentz and Townsend, 2003), and the leafhopper *Carneocephala floridana* feeds preferentially on salt-marsh cord grass (*Spartina alterniflora*) that is fertilized with high levels of N (Rossi and Strong, 1991). In both studies the N concentration of the leaves was proposed to be a good indicator of susceptibility to leafhopper attack. Increased splitting is caused by high sidedress N applications in mid-July (Bienz, 1965), and it is possible that preplant N could cause similar effects if little leaching into the subsoil occurs. Furthermore, carrot cracking at harvest is increased at above optimum preplant N application rates (Hartz et al., 2005).

The only effect of N application rate on storability occurred in 2003 on mineral soil. This effect is probably due to the small size of some of the roots in the low N treatments, which lost moisture rapidly and became susceptible to storage diseases such as bacterial soft rot. It could be concluded from these results, that early season N application had little or no effect on carrot quality or storability other than the effects on root size and stand, and this confirms previous reports (Burdine and Hall, 1976; Nilsson, 1979; Westerveld, 2002).

2.4.2 Effects of N Timing and Sequence on Carrot Yield and Quality

Preplant N always had more effect on yield and quality than sidedress N applications. However, sidedress N did improve yields over no N application in some cases. In addition, there were no benefits to adjusting the sequence of N application over the three years. Application of varying amounts of sidedress N on mineral and organic soil in the foliar spray trials did not result in improved yield over similar preplant N rates in any case. However, sidedress of 200% of the recommended rate on mineral soil resulted in an increase in split roots, which were considered culls at harvest. The late fertilizer application likely caused a rapid increase in growth of the root that resulted in a split. Similar effects of sidedress N (Bienz, 1965) and late season irrigation (Gracie and Brown, 2004) on root splitting have been observed, a result attributed to rapid secondary growth of the root. However, since no yield response occurred on the site in 2004, it is unknown how sidedress N would have caused rapid growth of the storage root. Overall, sidedress N and split N application were not as beneficial as preplant N on mineral or organic soils. This effect could be due to deep rooting early and N uptake from deep in the soil profile, and there may have been insufficient time for sidedress N to leach into

the active rooting zone before the period of peak N uptake. Rooting depth, N uptake distribution, and the period of peak N uptake are discussed below. The usefulness of sidedress N may be improved through optimal irrigation after application, since it would leach N into the rooting zone. No irrigation was available for these experimental plots.

2.4.3 Effects of Foliar N Application on Carrot Yield and Quality

Foliar N application with surfactant increased yields slightly in two of the six trials. On organic soil in 2004, all three treatments receiving foliar sprays with surfactant had higher yields than the no N control treatment, and there was no effect of preplant N rate on total yield, except that yields declined slightly at the recommended N rate preplant. This suggests that the foliar N application caused most of the effects observed. Foliar N application appears to provide some benefits in terms of yield even if preplant N does not have an effect. It is unknown why similar yield responses did not occur in the other years. The timing of foliar N application within the day may be important. While all applications were applied prior to noon on each application day, it is possible that the timing of application may have been different among years or weather conditions may have affected the speed of leaf drying and the uptake of N as a result. Application of foliar N under conditions that would increase absorption such as dawn or dusk application could improve N uptake and improve the efficacy of foliar N application. A surfactant is necessary to improve N uptake into the leaves. Preplant N appears to have a more substantial effect on yield than foliar N application.

2.4.4 Sap Nitrate Concentration

Sap NO_3-N concentrations were not increased by foliar N application. Nitrogen absorbed by the leaves would be converted to organic forms before being transported to the roots (Salisbury and Ross, 1992). However, sap NO_3-N concentrations were examined over the season in these plots to track changes in the transport of NO_3-N over the season as affected by foliar treatment. The early-season sampling date occurred prior to the foliar sprays. In the other two sampling dates there were no differences between the no N control treatment and the no preplant N treatment given biweekly foliar sprays. However, sap NO_3-N concentrations were numerically lower in the foliar spray treatment 80% of the time. It is possible that foliar N application improves leaf N status, reducing the need for NO_3-N to be transported from the roots to the leaves. All of the significant effects of treatment on NO_3-N concentrations can be attributed to differences in preplant N rate.

Overall, consistent critical sap NO_3-N concentrations that could be used to adjust fertilizer applications could not be identified. This work indicated that critical sap NO_3-N concentrations were cultivar specific and varied with soil type. Petiole sap NO_3-N concentrations generally increased with increasing N application rate, indicating that some luxury N consumption may have been occurring in these plots. Since there was no yield response in any of the three years on organic soil, the lowest NO_3-N concentration was assumed to represent a critical NO_3-N concentration. However, the actual critical concentrations could be much lower than the levels determined based on this research. Although the yield response in 2003 and 2004 on mineral soil provided a good indication of N sufficiency, the critical NO_3-N concentrations established were highly variable among years, and different from those determined for organic soil. Perhaps a yield

response occurred on mineral soil that could not be identified because of spatial variability in the plots. If a quadratic relationship between N rate and yield was assumed for both the 2002 and 2003 season, the critical concentrations for mineral soil would become slightly more consistent among years for the early sampling date (566-619 $mg \cdot kg^{-1}$ NO_3-N). However, the research required to establish a critical NO_3-N concentration for each cultivar on each soil type, given the variability among years, would be excessive and costly.

It is not clear why there was so much variability in critical NO_3-N concentrations among years. It is possible that crop growth was limited by another factor such as rainfall or deficiency of another nutrient other than N in some years, which would make sap NO_3-N concentrations less relevant for the determination of yield potential. Wilting was observed in some years on mineral soil. Furthermore, a comparison between tissue nutrient concentrations and published critical concentrations (Maynard and Hochmuth, 1997) for carrot leaves at harvest suggests that slight deficiencies of P, Mg, Zn, and Mn may have occurred on the mineral soil site in 2003 and 2004. It is also possible that wilting of leaves caused increased NO_3-N concentrations due to a concentrating effect. Another possibility is that critical NO_3-N concentrations are highly dependent on the growth stage of the carrot (Westerveld et al., 2003b). Sap NO_3-N concentrations clearly decline over the growing season, especially during the early and mid-season sampling stages. Weather conditions in general and early season temperatures in particular were highly variable among years. Carrots may have been at different physiological growth stages at the same DAS due to variability in their development caused by weather conditions during the first few months after seeding. Combined with variability in

sampling dates, this could partially explain the variability. Days after seeding was found by Strandberg (2001) to be most appropriate as an indicator of carrot growth stage, since carrots have no defined growth stages during the first year of growth. Given that growers are unlikely to track degree-days over the season and to match them with NO_3-N concentrations, that there is high variability among years, and that every soil type and cultivar would have to be monitored separately, it is unlikely that sap NO_3-N concentrations can be useful for grower N management of the crop. However, since a significant correlation between Cardy meter NO_3-N concentrations and laboratory results existed in most cases, and previous research has shown similar results (Westerveld et al., 2003), the Cardy meter can be a useful tool for comparison among treatments or cultivars for experimental or modelling purposes.

2.4.5 Soil Nitrate Concentration

Soil NO_3-N concentrations were much more consistent than sap NO_3-N concentrations, and increased linearly with N rate in most cases. Making the same assumption as for sap NO_3-N that a yield response may have occurred that was not identified due to spatial variability in the plots, the critical soil NO_3-N concentrations at the early sampling date would also become more consistent (31.1 – 42.6 $mg \cdot kg^{-1}$). The highest of these critical levels occurred on organic soil in 2002 and 2003. Since no yield response occurred in these years, indicating N sufficiency, it is likely that the actual critical concentrations were lower. Consequently, using the assumption of a quadratic yield response, a critical concentration of between 31.1 and 36.1 $mg \cdot kg^{-1}$ would be representative of all six plots at the early sampling date. Critical soil NO_3-N concentrations at the other two sampling dates were much more variable. It is possible

that soil NO_3-N concentrations are less important for crop nutrition at these dates. It is also possible that the dry conditions that occurred later in the season in most years contributed to deep rooting, resulting in less N uptake from the top 30 cm of the soil profile, where the soil samples were collected. The early sampling stage is usually regarded as the most critical stage for N monitoring, since there is still time to fertilize the crop and correct N deficiencies, as long as sufficient rainfall or irrigation is provided to leach added N into the active root zone.

Although soil NO_3-N concentrations determined by the Cardy meter and laboratory analysis were closely related, the conversion factors between Cardy readings and laboratory results were highly variable, especially on organic soil. Some of this variability was due to differences in laboratory NO_3^- extraction procedures among the years. Laboratories would have to standardize all aspects of testing procedures for organic soils before soil N monitoring could be a useful tool in Ontario. Soil NO_3-N results as determined by the laboratory were much more variable than Cardy meter readings, a result that was mostly due to a few anomalous results that dramatically influenced the reported means but were not identified as outliers during statistical analysis. There is often major spatial variability in soil NO_3-N concentrations (Kachanoski and Fairchild, 1996), and it is possible that this variability and incomplete mixing of the samples prior to analysis caused the anomalous samples.

Preplant soil NO_3-N concentrations in the top 30 cm did not provide a good indication of crop N fertility. Since the soil testing procedures were different between the laboratories, it is not possible to determine if preplant NO_3-N could have been useful for adjusting N fertilizer application to carrots. Overall, this research indicates that soil NO_3-

N monitoring of the carrot crop, using a Cardy NO_3^- meter, can provide a good indication of yield potential at the time of sidedress N application, and could be effectively used to adjust fertilizer applications to correct crop N deficiencies. This research also supports earlier research that showed a strong correlation between Cardy meter readings and laboratory results (Westerveld et al., 2003). Further research on pre-season or early-season soil NO_3-N monitoring at various depths using laboratory results or the Cardy meter is warranted.

2.4.6 Rooting Depth and Distribution

Rooting depth and distribution of fibrous roots in the soil profile appear to be critical factors in the N uptake by carrots. Carrots grown in sand in pipes produced up to 55% of the fibrous root system below 30 cm below the surface. This is similar to previous reports from the field (Thorup-Kristensen and van den Boogaard, 1999). It was also shown that the distribution of N-uptake in the fibrous root system is proportional to the distribution of the roots in the soil profile. It is not known whether the root distribution in the greenhouse was similar to the distribution in the field, since the moisture profile of the field would be much different than in the pipes and since the confined area in the PVC pipes could have forced roots downward. However, observations of the rooting system in the pipes indicated that a large proportion of the roots that reached below 30 cm depth originated at the taproot and did not reach the perimeter of the soil column at any depth. This suggests that the deep rooting response was not induced by confinement in the cylinder. On the other hand, a large portion of the fibrous root system in the top 30 cm of the soil did reach the side of the pipe, but these roots encircled the cylinder rather than growing downward. Field observations on both

soil types indicated that fibrous roots were present at 90 cm below the soil surface in September, which coincided with the top of the water table at that time of the year. In addition, the subsoil on the mineral soil site was very similar to the pure silica sand used in the greenhouse experiments, and consequently, a large portion of N uptake probably occurred below 30 cm depth. This could account for the effect of soil residual N on yield in 2003. The results of these studies are supported by similar research conducted in Denmark during the same period. Carrots were grown in minirhizotrons in a loamy sand and a root depth of greater than 1 m was found (Kristensen and Thorup-Kristensen, 2004). Injection of ^{15}N at different depths in the soil profile resulted in amounts of N uptake that were proportional to the number of roots crossing the injection site (Kristensen and Thorup-Kristensen, 2004). The researchers in this study suggested that N in deep soil layers must be accounted for in studies conducted on deep-rooted crops such as carrots. Overall, these findings suggest that carrots require minimal applied N in the year it is applied because of N uptake from deep in the soil profile. Nitrogen monitoring may have to be conducted up to 60 cm depth to accurately depict N availability from the soil.

In soilless media, the rooting system was not as extensive. Less than 25% of the roots in this experiment occurred below 30 cm below the soil surface. These conditions would probably more closely resemble the rooting system on organic soil. Nutrients and moisture would have been more available to the roots in the soilless media, which would make additional root growth less of a necessity than in the sand. However, roots did reach down 1.2 m in some instances. In addition, field observations in September indicated roots at 95 cm below the surface in organic soil, which was 5 cm below the water table at

that date. The potential for deep N uptake is less on organic soil, and would be less necessary because adequate water and nutrients would be available in the top 30 cm during the entire growing season. The results in soilless media suggest that deep rooting cannot be the only explanation for the lack of yield response on organic soil, and it is likely that extensive mineralization of organic matter provides sufficient N for the crop, regardless of the location of the rooting system.

Nitrogen rate had little influence on the root system in carrots grown in sand. However, the dry weights of the top and storage root for 'Idaho' were highest at the recommended N rate and were reduced above and below that rate. In addition, the top weight to storage root weight ratio increased with increasing N rate. The storage root weight was also highest in comparison to root depth at the recommended rate. For both cultivars, the lowest top dry weight to total root weight ratio (shoot to root ratio) was lowest at the low N rate, but not significantly lower than the other two N rates. Consequently, although it appears that carrots partition more DM to the roots under deficient N conditions, there was too much natural variability to support this hypothesis.

The results for 'Idaho' match field findings on mineral soil that reveal a relatively narrow sufficiency zone for N. Application of more or less N than the optimum caused a dramatic decrease in the dry weight of the top and storage root. As in the field, most of the excess N effect in the pots can be attributed to damage in the seedling stage. This damage could have been due to damping-off, since damping-off was found in some of the seedlings that were removed during thinning. However, visual observations at the seedling stage suggest that the effect of high N could also have been due to damage of the root system directly by N toxicity. These findings are consistent with results in the field.

It is possible that damage of the rooting system or hypocotyl by direct N toxicity could have allowed an opportunity for the damping-off fungi to infect the seedlings and kill the plant. Therefore, based on both the field and greenhouse observations, high N probably results in seedling damage because of an increase in damping-off diseases, direct damage of the rooting system, or a combination of the two.

Both cultivars showed similar root distributions. Both cultivars also were similar in the uptake of ^{15}N. However, 'Fontana' carrots recovered more ^{15}N in the new leaves during the second application period in September than 'Idaho' carrots. This is surprising since 'Idaho' carrots were observed in the field to produce new leaves for a much longer period late in the season than 'Fontana' carrots, and new leaf production would result the largest recovery of N. These results suggest that there are only minimal differences in the patterns of N uptake between the cultivars over the growing season. Consequently, differences in N partitioning to the leaves between the cultivars do not provide an explanation for the differences in leaf blight susceptibility. Thus, other factors such as differences in defence structures and compounds or organic N constituents in the plant must be involved.

2.4.7 Critical Period for N Uptake

The important finding from this study was the large proportion of total N that was taken up during a three-week period. Up to 67% of total N in the leaves and 54% of total N in the storage root were derived from ^{15}N-enriched fertilizer applied at 74 DAS. This appears to be a critical period for N uptake. In addition, up to 40% of the N in the new leaves and 24% of the storage root N were recovered during the three-weeks following the second application of ^{15}N-enriched fertilizer applied at 97 DAS. This period of

growth only accounted for 18% of the growing period up to that point. Hence, the majority of the N was taken up between 74 and 118 DAS. This would be when carrot had the most extensive root system and the largest canopy. Carrots have been shown to exhibit very slow development over the first month of growth (Markovic et al., 2002), and it is likely that little N is taken up during this period.

In both assessments, the largest proportion of total N derived from ^{15}N-enriched fertilizer occurred in the new leaves, followed by the storage root, and the lowest proportion was recovered in the old leaves. These results match observations made during injection of safranin O dye, which revealed that dye injected below the storage root is located entirely within the vascular tissues after uptake. The results suggest that the N taken up by the roots below the storage root is delivered to the leaves first and then transported back to the roots. This confirms earlier reports showing that the primary location of NO_3^- reduction by NO_3^- reductase is in the leaves in carrots (Darwinkel, 1975).

2.4.8 Nitrogen Use Efficiency

The results reveal that carrots exhibit high NUE, since yield and quality can be maximized without N application in all cases on organic soil and in one of three cases on mineral soil. However, this apparent high NUE appears to be mainly due to uptake of mineralized and residual N from deep in the soil profile that is not accounted for in the agronomic definition of NUE (DM produced per unit N applied (Lynch, 1998)). Furthermore, the yield response up to 200% of the recommended rate on mineral soil in 2004 suggests that NUE might not be high. Measurements of N uptake over the season

and partitioning to the harvested portion are required before the hypothesis that carrots exhibit high NUE can be fully tested.

2.5 Conclusions

Nitrogen uptake, partitioning, and utilization were studied for two soil types and two cultivars over a three-year period in which N was applied as a preplant treatment, sidedressed, and as a foliar spray. The N requirements of carrots for optimum storage root yield varied depending on the climate, soil, cultivar, residual soil N from the previous season, and soil mineralization rate. Residual N had more effect on yield than preplant applied N in 2003 on mineral soil, and preplant N had more effect on yield than sidedress or foliar-applied N. This was attributed to uptake of N from deep in the soil profile and increasing depth of N due to leaching over time. There were no effects of applied N on storage root quality or storability. Predicting the N requirements of the crop was not possible using sap NO_3-N concentrations. Soil NO_3-N concentrations provided a good indication of yield potential early in the season using a Cardy NO_3^- meter soil testing procedure, but only when assuming a quadratic yield response to N application rate occurred on mineral soil in both 2002 and 2003. Carrots were shown to require 166 $kg \cdot ha^{-1}$ in the top 60 cm of the soil profile at seeding to produce maximum yield in mineral soil. Foliar N application increased yield in one of three years for both soil types. Over-application of N caused major losses due to seedling damage on mineral soil in 2003 and 2004 and occurred at N rates that provided optimal yields in other plots or previous years. Thus, methods of determining the risk of excess N prior to seeding are required to avoid crop losses. Carrots were shown to have a deep rooting system (11.3-61.4% of roots below 30 cm depth), and it was also shown that deep roots are capable of

taking up as much N as the roots close to the soil surface. The majority of N is taken up during the months of August and September, and proper N fertility is essential in the active root zone during this period. Since carrots required little N in four of six plots for organic and mineral soil to optimize yield and quality, the first hypothesis that carrots exhibit high NUE is supported by this research, but the results suggest that this high NUE is mainly due to extraction of N from deep in the soil profile that is not accounted for in the calculation. The second hypothesis that the susceptibility of cultivars to leaf blight is due to differences in N partitioning in the plant is not supported by this research, since there were no differences in N partitioning between the cultivars.

Chapter 3: Uptake and Partitioning of Nitrogen by Carrots over the Growing Season as Affected by Nitrogen Application Rate, Soil Type, and Cultivar

Abstract

In order to determine the patterns of nitrogen (N) uptake and partitioning in the carrot crop and plant and to test the N use efficiency (NUE) of the crop, experiments were conducted on organic and mineral soil to track the accumulation of DM and N over the season and to develop an N budget of the carrot crop. Carrots cvs. 'Idaho' and 'Fontana' were seeded into organic and mineral soil on the same site for three years. Nitrogen was applied at 0, 50, 100, 150, and 200% of the recommended N rates in Ontario. Top and root samples were collected from selected treatments and cultivars biweekly on seven dates beginning at the end of July and ending at harvest. Samples were dried, weighed, and assessed for total N concentration. Harvest samples were used to calculate N uptake, N in debris, N removal, and net N removal values. Accumulation of DM and N in the roots was low until 50 to 60 days after seeding (DAS) and then increased linearly until harvest for all years, soil types, cultivars, and treatments. Top dry weight and N accumulation were more gradual before 50 to 60 DAS, increased linearly between 50 and 100 DAS, and reached a maximum or declined slightly beyond 100 DAS in most cases. The N application rates required to maximize yield on mineral soil resulted in a net loss of N from the system, except when sufficient N was available from the soil to produce optimum yield. On organic soil, a net removal of N occurred at all N application rates and in all years. Carrots could be used as an N catch crop to reduce N losses in a vegetable rotation on organic or mineral soil in conditions of high soil residual

N. The high NUE of carrots is mainly due to uptake of mineralized and residual soil N that is not accounted for in the calculation, because carrots have low fertilizer N recovery rates in N deficient conditions.

3.1 Introduction

Knowledge of the patterns of uptake and partitioning of nitrogen (N) and the production and partitioning of dry matter (DM) in the carrot crop over the growing season could be useful in identifying periods of peak N uptake and in adjusting fertilization practices accordingly. Carrots are known to begin forming the storage root between 13 and 34 DAS (Esau, 1940; Hole et al., 1987a; Hole and Dearman, 1991). Between 34 and 65 DAS there is a slow increase in top and root DM (Hole et al., 1983). This is followed by a rapid linear increase in root dry weight from 65 DAS until harvest (Platenius, 1934; Rubatzky et al., 1999; Reid and English, 2000; Strandberg, 2001), and a linear increase in top DM beginning slightly earlier and reaching a plateau or declining beyond 100 DAS (Platenius, 1934; Rubatzky et al., 1999). Nitrogen accumulation in the carrot plant is slow over the first 30 DAS and then increases at a rapid rate until harvest (Salo, 1999).

No studies have examined the dynamics of N uptake and partitioning over the growing season or have developed an N budget at harvest as affected by N application rate, cultivar, and soil type. This information would be useful in identifying the periods of peak N uptake and explaining how uptake patterns change depending on N availability. Strategies to improve the N use efficiency (NUE) of the carrot crop could then be developed in order to reduce N losses and help growers cope with strict environmental laws outlined in the Nutrient Management Act (NMA)(O.M.A.F., 2005). Nitrogen use

efficiency is defined as the DM produced in the harvested portion of the plant per unit N applied (Lynch, 1998). In addition, differences among N application rates and cultivars in uptake and partitioning of N and N content might explain differences in disease susceptibility and yield. An N budget of the carrot crop could be used to determine the potential use of carrots in a rotation as an N catch crop and would assist in the development of nutrient management strategies. Nitrogen catch crops are crops used for the purpose of removing excess nutrient from the soil (Fream, 1905).

The purpose of this experiment was to develop an N budget of the carrot crop and to test the following hypotheses by monitoring carrot top and root dry weight and N accumulation over the season using different N application rates, cultivars, soil types, and years.

1. Carrots exhibit high NUE.

2. The ALB susceptibility of different carrot cultivars and carrots grown at varying N application rates is influenced by the partitioning of N in the host plant, whereas that of CLB is not.

3.2 Materials and Methods

3.2.1 Nitrogen Uptake and Partitioning

Nitrogen rate experiments were established as described in Chapter 2. All samples were collected from the half of each plot receiving N for three consecutive years (annual fertilizer section). When the plants were large enough to collect samples (tops 15 cm high; roots > 0.5 cm diameter) in mid-July, samples were collected from three replications biweekly until two weeks before harvest in 2003 and 2004. Plant samples

consisted of tops and roots of six plants (10 plants for early sampling dates on mineral soil) taken from two separate locations within the middle two rows of each cultivar. Fibrous or deep taproots were not collected. Samples were collected from 'Idaho' carrots on all six sampling dates in 2003 and 2004 from the no N and recommended N rate treatments, and from 'Fontana' carrots from the same treatments at the first (first and second in 2003) and fourth sampling dates. At harvest in 2002, samples were collected of both cultivars from the recommended rate treatment only. In 2003, samples were collected from three replications of the treatments at 0, 100, and 200% of the recommended N rate. In 2004, samples were collected from all rates, replications, cultivars, and soil types. All samples were dried at 70^{o}C for 48 h, weighed, and sent to the University of Guelph, Soil and Nutrient Laboratory (2002 and 2003) and A&L Laboratories East Inc. (2003 and 2004) for total N analysis. Total N concentration was determined by automated dry combustion procedures by both laboratories (Shepers et al., 1989). The amount of N supplied as NO_3-N in rainfall was estimated to be 8 kg·ha^{-1}·season^{-1} based on NO_3-N assessments of rainfall throughout the season in a previous study (Westerveld, 2002). Rainfall over the growing season in the previous study was 319 mm·season^{-1}, which is comparable to 289-374 mm·season^{-1} in this study.

Results were converted to a per hectare basis by factoring in yield and stand at harvest, which were determined as described in Chapter 2. Nitrogen use efficiency (NUE) and fertilizer N recovery (FNR) were calculated for the N application rates that maximized yield in Chapter 2 and for the highest N application rate using the following equations, where NAR is the N application rate (all variables in kg·ha^{-1}):

$$NUE = \frac{\text{(dry weight of roots at NAR)}}{\text{(N applied in NAR)}}$$

$$FNR = \frac{(\text{N in storage root at NAR}) - (\text{N in the storage root at 0 N rate}) * 100}{(\text{N applied in NAR})}$$

3.2.2 Statistical Analysis

An analysis of variance was performed on each data set to partition the variance into treatment, block, cultivar, soil type, and year effects, where applicable, and to identify interactions among these effects. The entire data set for each assessment was assessed for normality using the Shapiro-Wilk test of residuals. Outliers were identified using Lund's test of standardized residuals (Lund, 1975). Data were analysed over time and over N rate by linear and quadratic regression analysis using the PROC GLM, PROC CORR, PROC PLOT, and PROC Univariate procedures of SAS version 8.0 (SAS Institute, Cary NC). A type I error rate of 0.05 was set for all statistical tests.

3.3 Results

Dry matter accumulation in the roots was generally linear after 53 DAS on organic soil in 2003 (Figure 3.1), after 66 DAS on organic soil in 2004 (Figure 3.2), after 53 DAS on mineral soil in 2003 (Figure 3.3), and after 67 DAS on mineral soil in 2004 (Figure 3.4) for both 'Idaho' and 'Fontana' at both N rates tested. Accumulation was best described by a quadratic equation with a slight decline in DM late in the season for 'Idaho' in the recommended N treatment on organic soil in 2004 (Figure 3.2), 'Idaho' in the no N treatment and 'Fontana' in the recommended N treatment on mineral soil in 2003 (Figure 3.3), and both cultivars in the no N treatment on mineral soil in 2004 (Figure 3.4). There was no significant trend in DM accumulation for 'Fontana' at the recommended N rate on mineral soil in 2004 (Figure 3.4). Less than 5% of the DM accumulation occurred prior to the first sampling date for organic soil (Figures 3.1 and

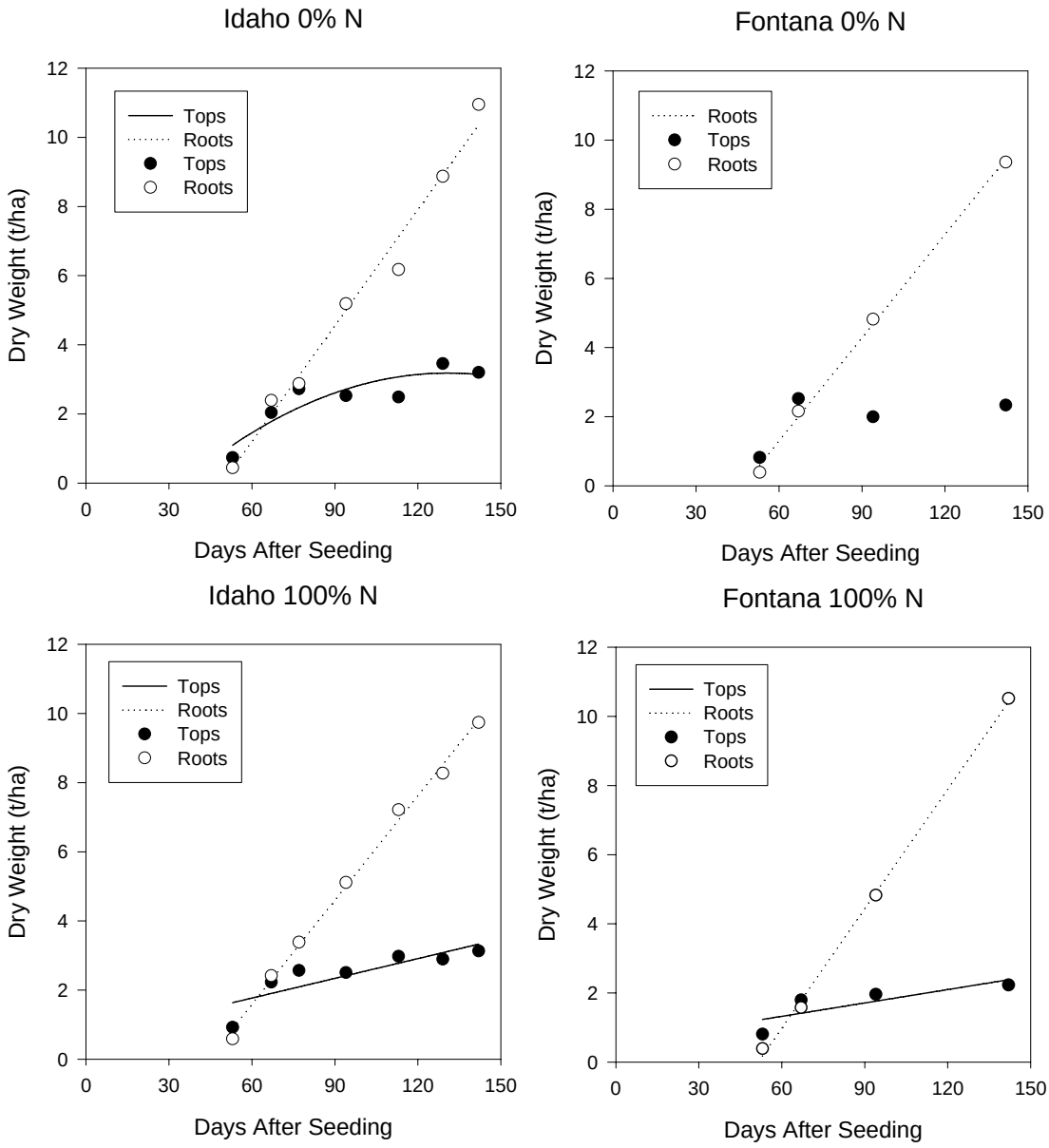

Figure 3.1. Dry matter accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on organic soil in 2003. Equations: 0% N Idaho Tops: R^2=0.65 Y=-2.7088+0.09002X-0.000344X^2; 0% N Idaho Roots: R^2=0.90 Y=-5.5095+0.1118X; 0% N Fontana Tops: Not Significant; 0% N Fontana Roots: R^2=0.98 Y=-4.6693+0.09945X; 100% N Idaho Tops: R^2=0.51 Y=0.6258+0.01903X; 100% N Idaho Roots: R^2=0.88 Y=-4.4447+0.10049X; 100% N Fontana Tops: R^2=0.43 Y=0.5483+0.01291X; 100% N Fontana Roots: R^2=0.98 Y=-5.9255+0.11511X.

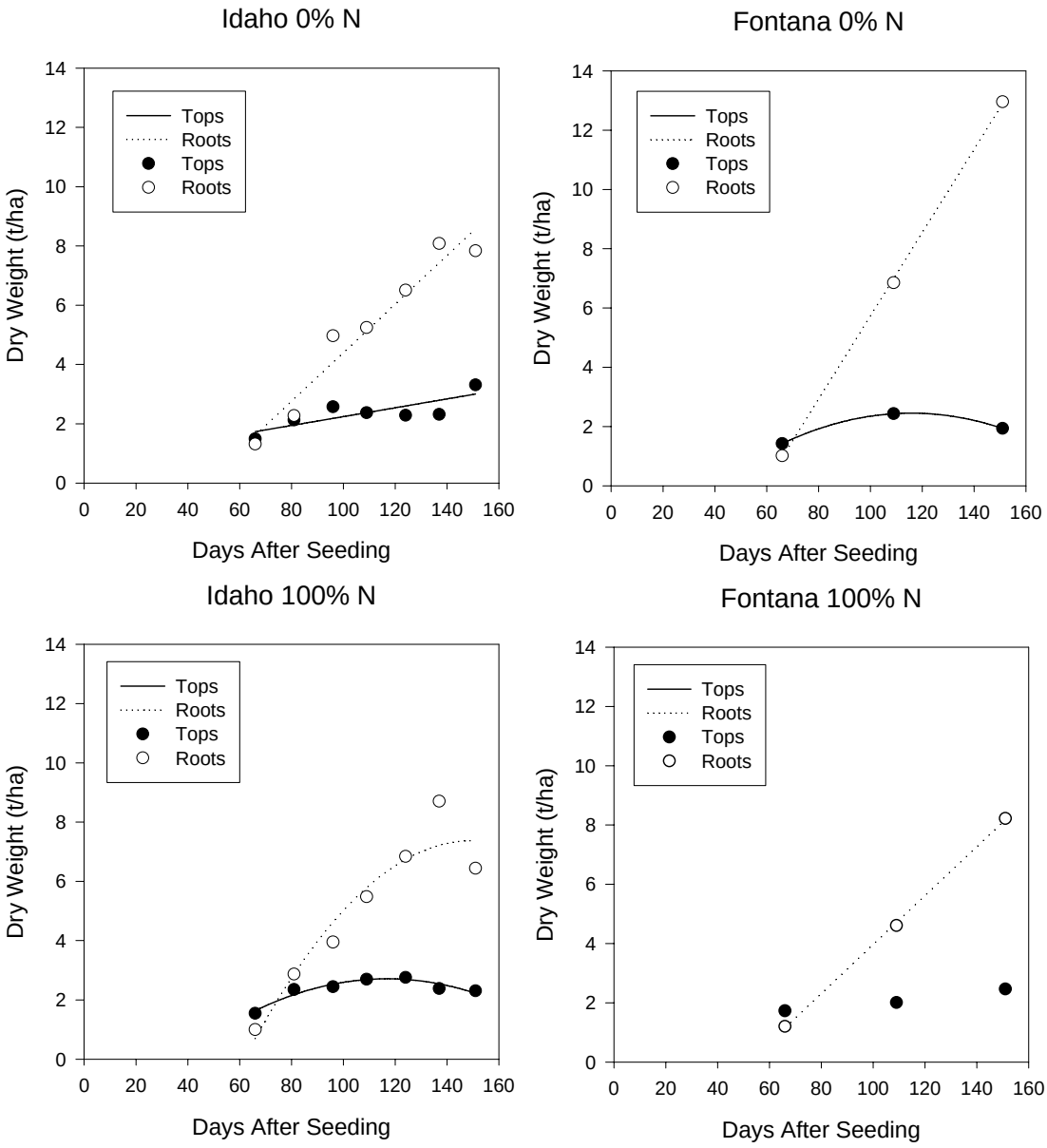

Figure 3.2. Dry matter accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on organic soil in 2004. Equations: 0% N Idaho Tops: R^2=0.41 Y=0.7487+0.01492X; 0% N Idaho Roots: R^2=0.84 Y=-3.8032+0.08199X; 0% N Fontana Tops: R^2=0.57 Y=-3.1091+0.09606X-0.0004149X^2; 0% N Fontana Roots: R^2=0.92 Y=-8.3225+0.1405X; 100% N Idaho Tops: R^2=0.33 Y=-2.9801+0.09745X-0.0004171X^2; 100% N Idaho Roots: R^2=0.67 Y=-13.957 +0.2847X-0.0009497X^2; 100% N Fontana Tops: Equation Not Significant; 100% N Fontana Roots: R^2=0.94 Y=-4.2975+0.08260X.

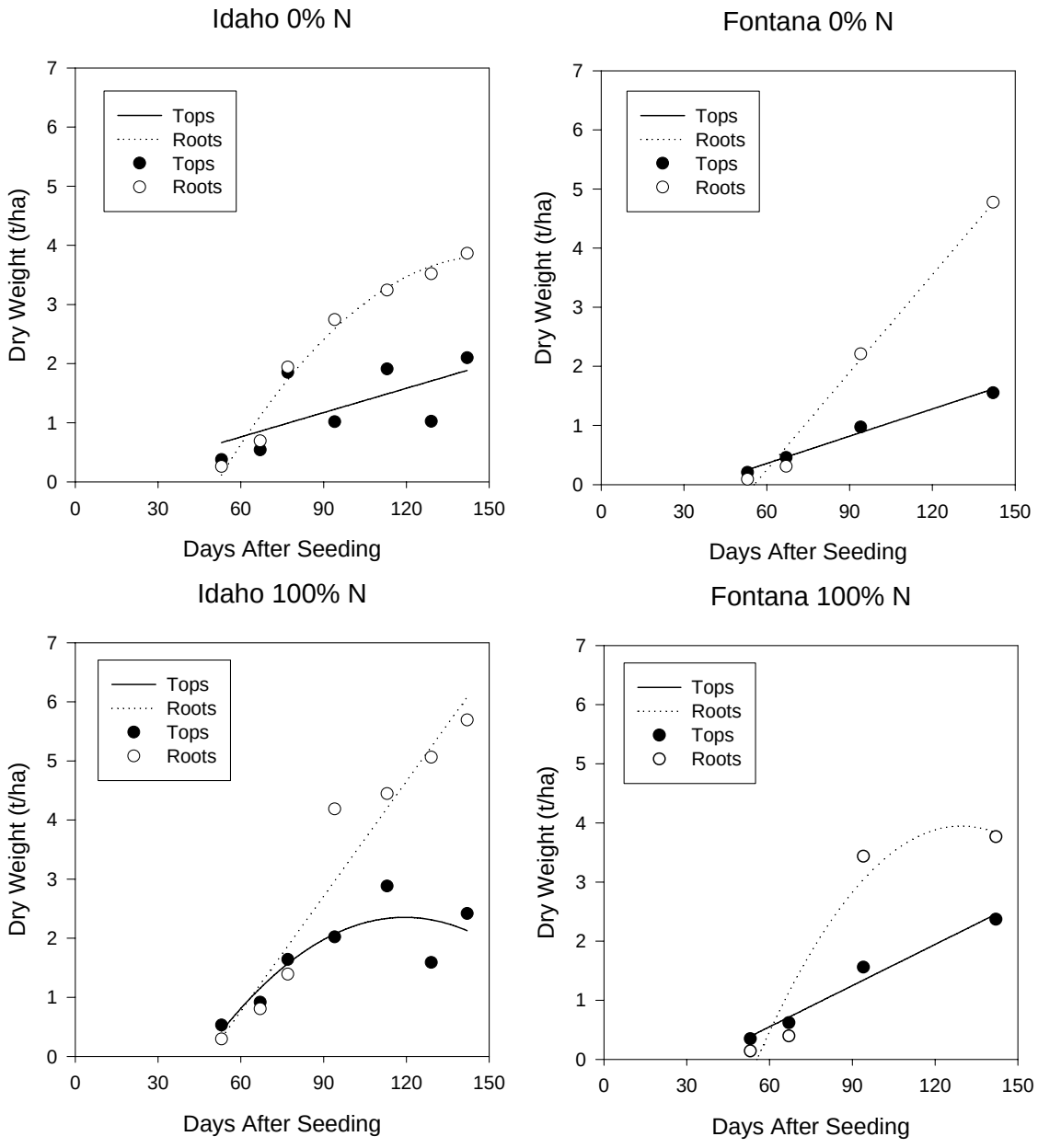

Figure 3.3. Dry matter accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on mineral soil in 2003. Equations: 0% N Idaho Tops: R^2=0.27 Y=-0.06384+0.01372X; 0% N Idaho Roots: R^2=0.66 Y=-5.0585+0.1186X-0.0003965X^2; 0% N Fontana Tops: R^2=0.88 Y=-0.5636+0.01536X; 0% N Fontana Roots: R^2=0.96 Y=-3.0522+0.05502X; 100% N Idaho Tops: R^2=0.56 Y=-3.8775+0.1044X-0.0004376X^2; 100% N Idaho Roots: R^2=0.76 Y=-3.1220 +0.06479X; 100% N Fontana Tops: R^2=0.80 Y=0.8425+0.02322X; 100% N Fontana Roots: R^2=0.78 Y=-8.1432+0.1868X-0.0007219X^2.

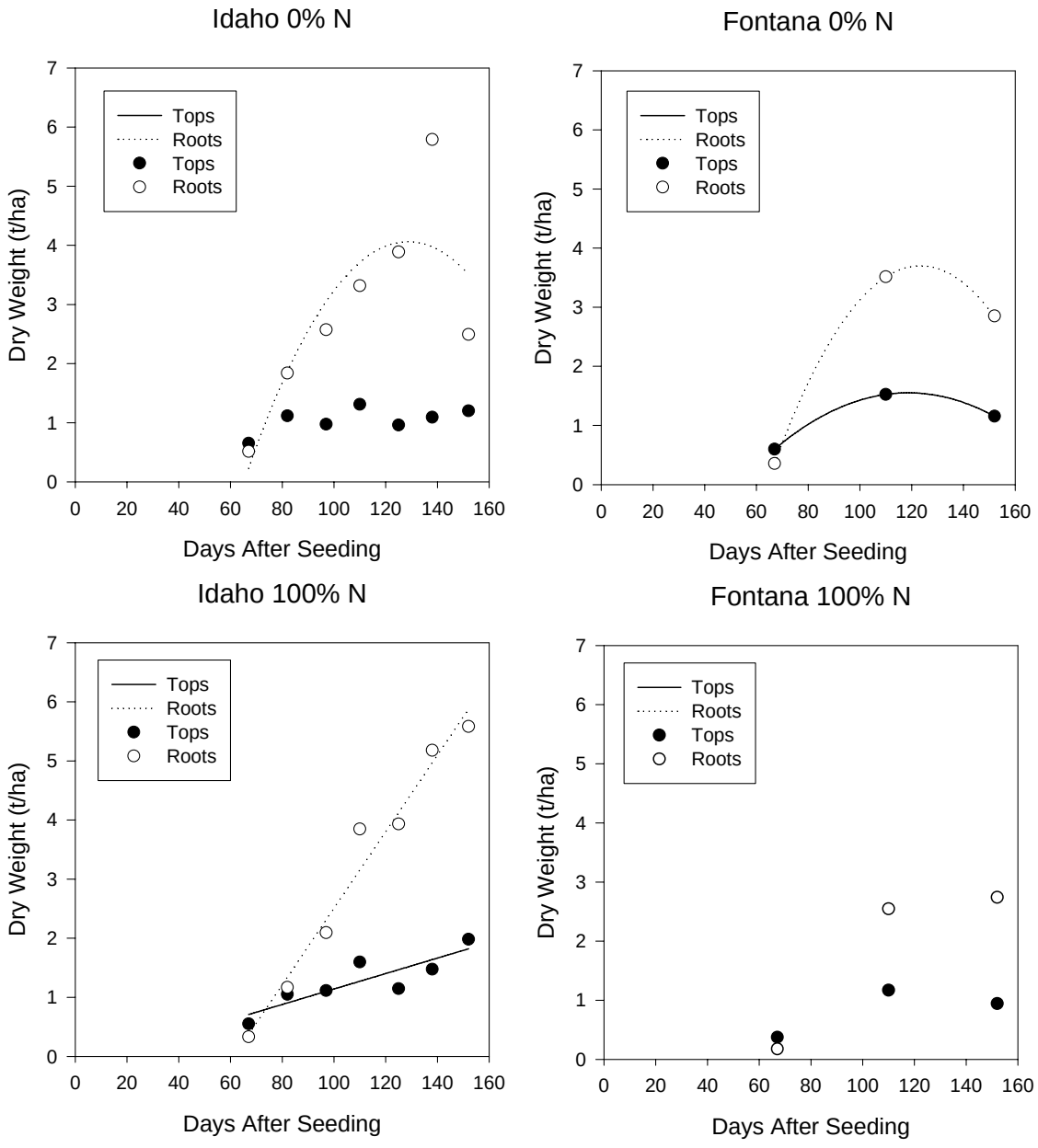

Figure 3.4. Dry matter accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on mineral soil in 2004. Equations: 0% N Idaho Tops: Not Significant; 0% N Idaho Roots: R^2=0.65 Y=-12.636+0.25961X-0.001009X^2; 0% N Fontana Tops: R^2=0.78 Y=-3.4726+0.08467X-0.0003567X^2; 0% N Fontana Roots: R^2=0.89 Y=-12.3102+0.2594X-0.001051X^2; 100% N Idaho Tops: R^2=0.46 Y=-0.1670+0.01308X; 100% N Idaho Roots: R^2=0.71 Y=-3.9713 +0.06477X; 100% N Fontana Tops: Not Significant; 100% N Fontana Roots: Not Significant.

3.2), but since the first date was later on mineral soil, more DM accumulated prior to the first sampling date (Figures 3.3 and 3.4). Dry matter accumulation was more gradual on mineral soil than on organic soil.

Dry matter accumulation in the tops was greater than in the roots by the first sampling date and increased gradually, levelled off, or declined slightly thereafter (Figures 3.1, 3.2, 3.3, and 3.4). In cases where DM in the tops declined late in the season, the peak DM content occurred between 115 and 135 DAS. There were no consistent differences in the patterns of DM accumulation between the treatments, soil types, or cultivars, although 'Idaho' had slightly higher DM accumulation in the tops than 'Fontana' in most cases.

Total N accumulation in the roots was similar to DM accumulation in all cases, with rapid linear increase beginning 53 DAS for organic soil in 2003 (Figure 3.5), 66 DAS for organic soil in 2004 (Figure 3.6), 53 DAS for mineral soil in 2003 (Figure 3.7), and 67 DAS for mineral soil in 2004 (Figure 3.8) for both 'Idaho' and 'Fontana' at both N rates tested. However, the rate of increase in total N content in the roots did not decline near harvest in any case. In the tops, a greater proportion of N accumulated prior to the first sampling date than DM in most cases (Figures 3.5, 3.6, 3.7, and 3.8). In general N accumulation in the roots increased more rapidly for 'Fontana' than for 'Idaho' on organic soil (Figures 3.5 and 3.6), but the opposite was true on mineral soil (Figures 3.7 and 3.8). Although there were no significant trends for N accumulation in the tops in 12 of 16 cases, total N content appeared to level off or decline beyond 80 to 100 DAS in most cases. There was a more even distribution of N between the tops and roots on mineral soil (Figures 3.7 and 3.8) compared to organic soil (Figures 3.5 and 3.6). There

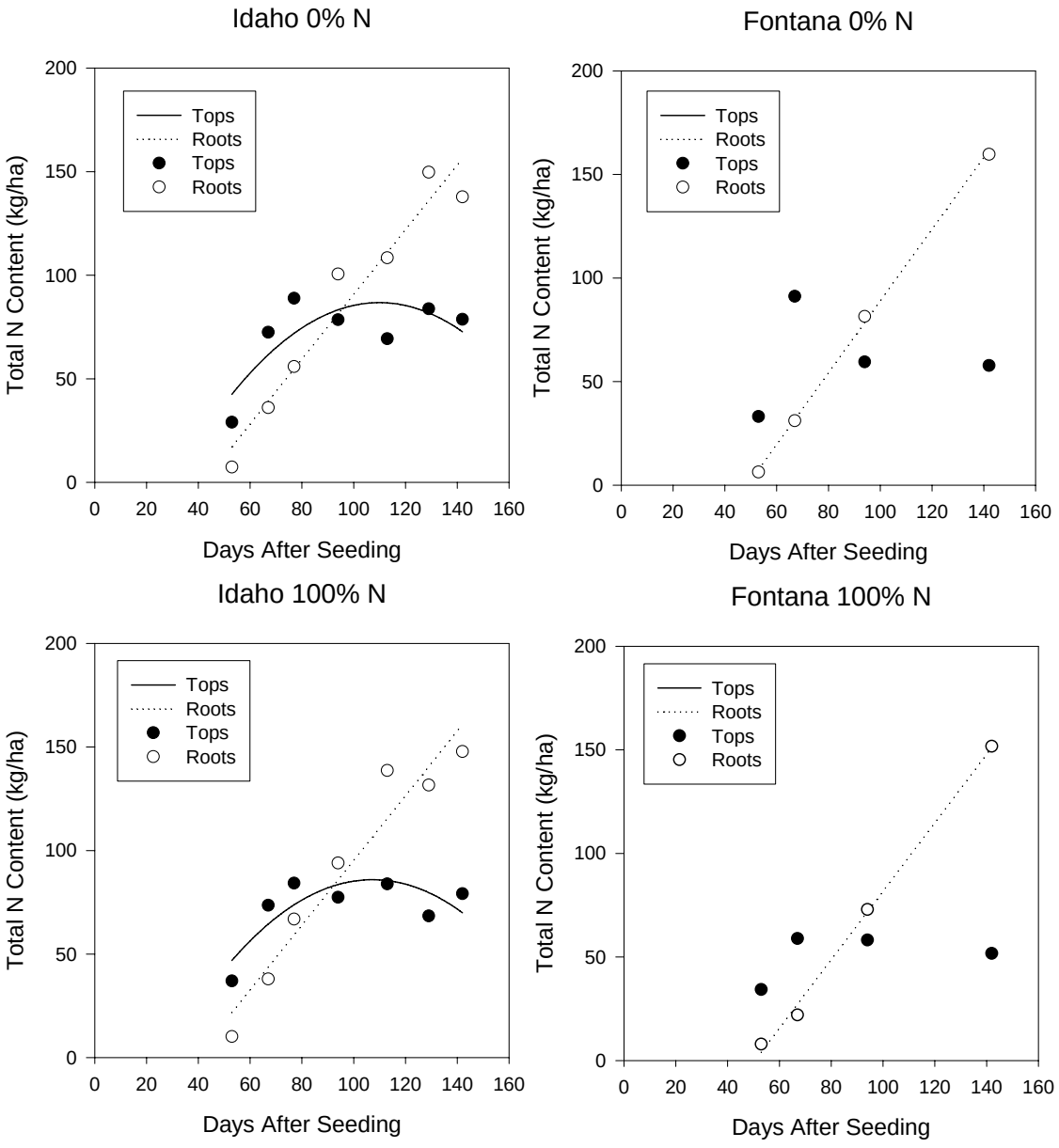

Figure 3.5. Total N accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on organic soil in 2003. Equations: 0% N Idaho Tops: R^2=0.33 Y=-78.1461+2.9998X-0.01364X^2; 0% N Idaho Roots: R^2=0.71 Y=-65.684+1.5636X; 0% N Fontana Tops: Not Significant; 0% N Fontana Roots: R^2=0.98 Y=-84.4885+1.7334X (outlier removed); 100% N Idaho Tops: R^2=0.41 Y=-66.402+2.8390X-0.01323X^2; 100% N Idaho Roots: R^2=0.77 Y=-61.127 +1.5626X; 100% N Fontana Tops: Not Significant; 100% N Fontana Roots: R^2=0.99 Y=-83.583+1.652X (two outliers removed).

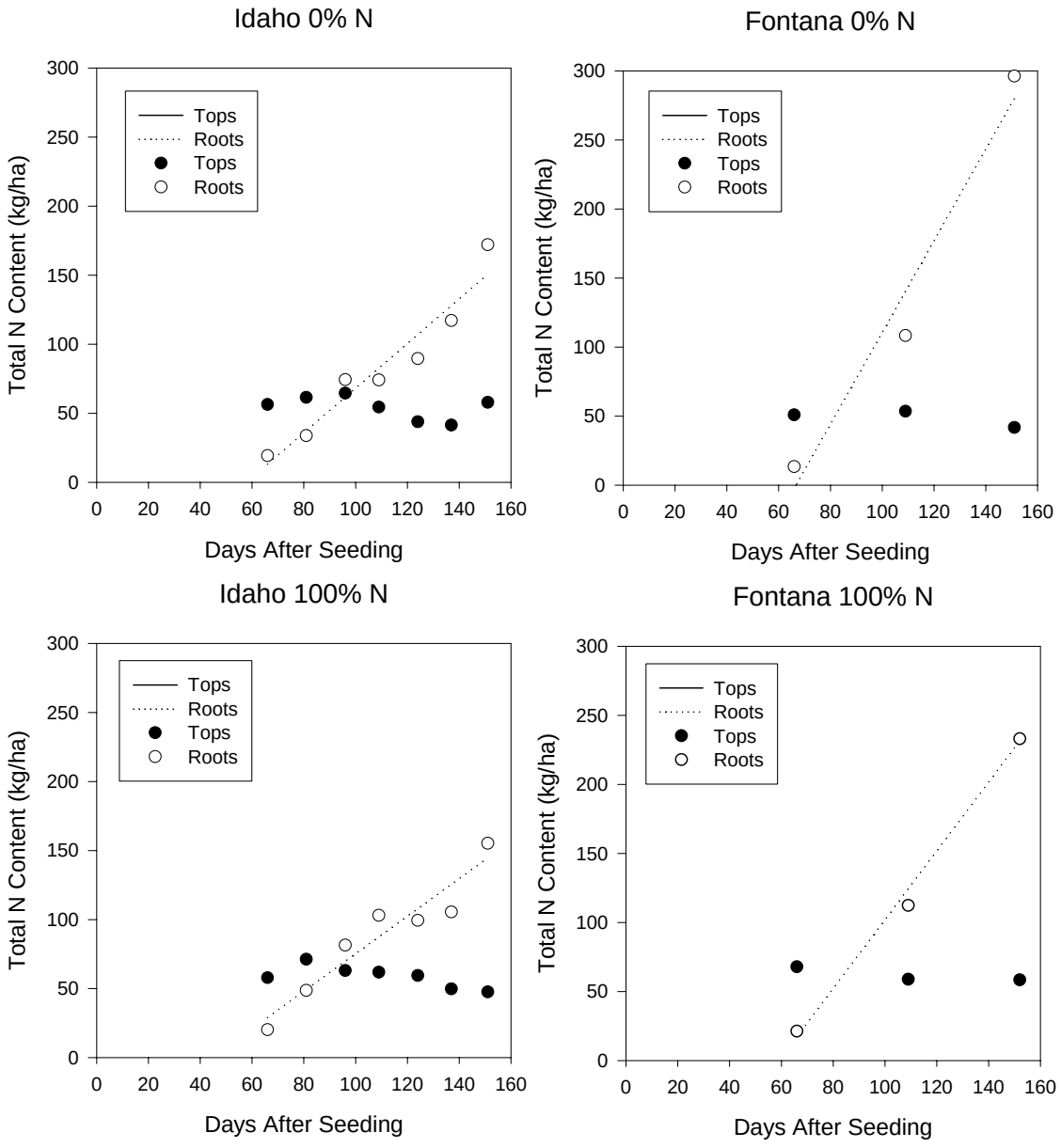

Figure 3.6. Total N accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on organic soil in 2004. Equations: 0% N Idaho Tops: Not Significant (outlier removed); 0% N Idaho Roots: R^2=0.79 Y=-93.660+1.6180X; 0% N Fontana Tops: Not Significant; 0% N Fontana Roots: R^2=0.89 Y=-221.83+3.3226X; 100% N Idaho Tops: Not Significant; 100% N Idaho Roots: R^2=0.78 Y=-60.7898+1.3597X; 100% N Fontana Tops: Not Significant; 100% N Fontana Roots: R^2=0.99 Y=-147.08+2.4897X (outlier removed).

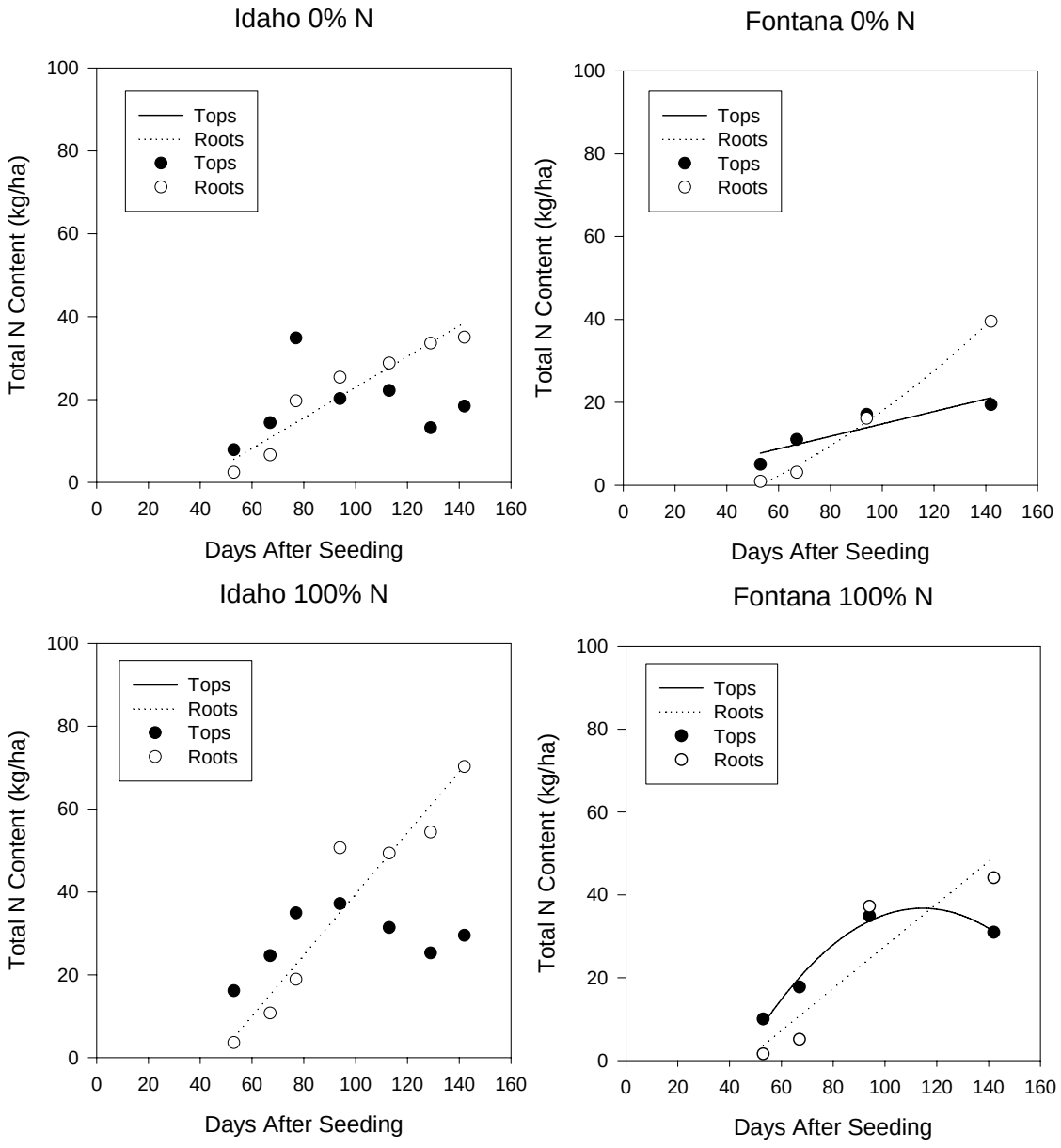

Figure 3.7. Total N accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on mineral soil in 2003. Equations: 0% N Idaho Tops: Not Significant; 0% N Idaho Roots: R^2=0.60 Y=-14.062+0.3701X; 0% N Fontana Tops: R^2=0.64 Y=-0.2532+0.1502X; 0% N Fontana Roots: R^2=0.99 Y=-12.014+0.1450X+0.001545X^2 (outlier removed); 100% N Idaho Tops: Not Significant (outlier removed); 100% N Idaho Roots: R^2=0.62 Y=-34.258+0.7374X (data does not follow a normal distribution; 100% N Fontana Tops: R^2=0.69 Y=-60.423+1.6976X-0.003747X^2; 100% N Fontana Roots: R^2=0.76 Y=-23.421+0.5103X.

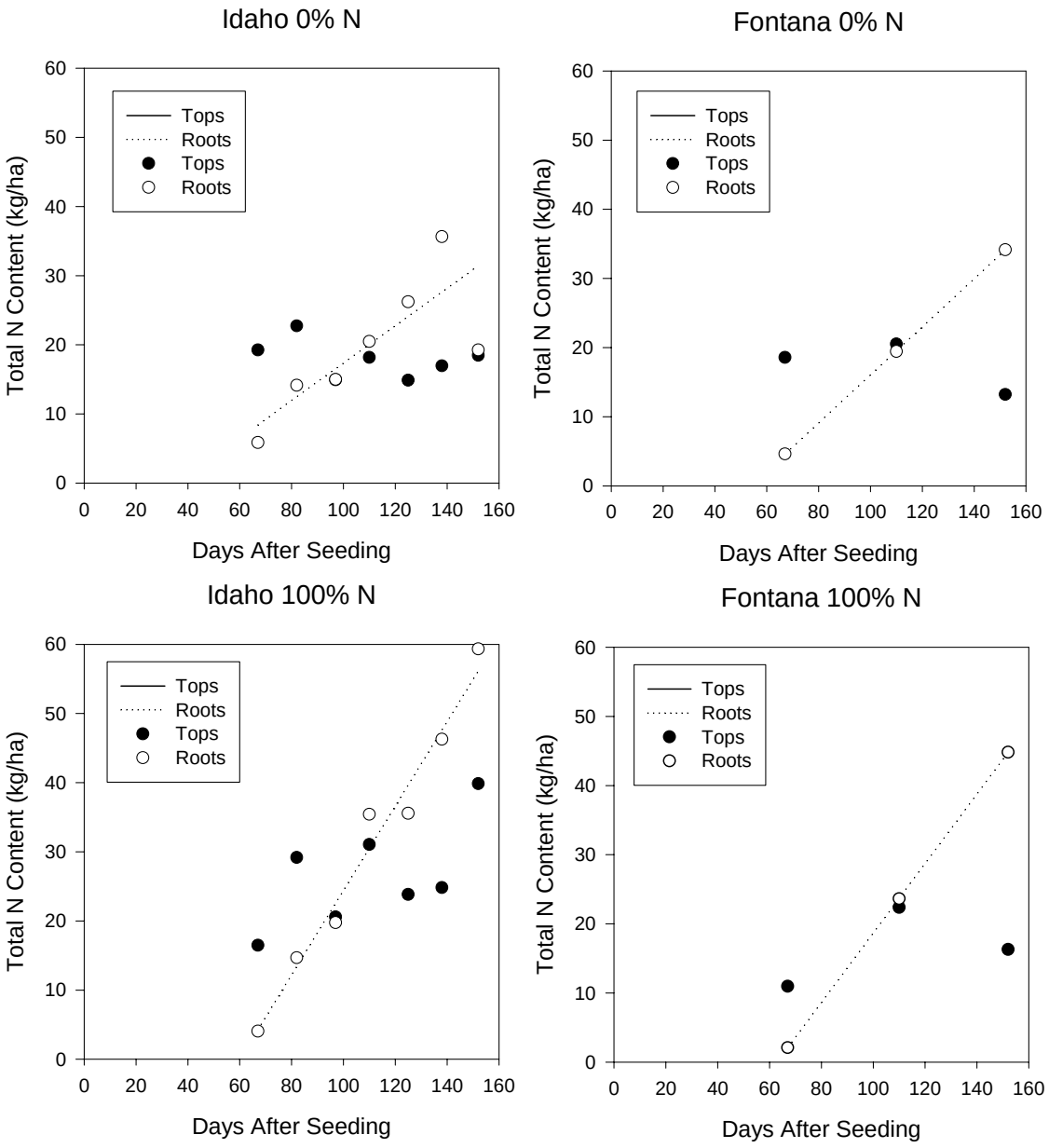

Figure 3.8. Total N accumulation during the growing season for tops and storage roots of Idaho and Fontana carrots grown on mineral soil in 2004. Equations: 0% N Idaho Tops: Not Significant; 0% N Idaho Roots: R^2=0.60 Y=-9.7007+0.2704X; 0% N Fontana Tops: Not Significant; 0% N Fontana Roots: R^2=0.90 Y=-18.709+0.3474X; 100% N Idaho Tops: Not Significant; 100% N Idaho Roots: R^2=0.80 Y=-36.660 +0.6103X; 100% N Fontana Tops: Not Significant; 100% N Fontana Roots: R^2=0.53 Y=-31.619+0.5026X.

were no differences in the patterns of N accumulation between the N rates on organic soil (Figure 3.5 and 3.6), but N accumulated more and at a faster rate after the first sampling date on mineral soil, especially in 2004 (Figures 3.7 and 3.8). More N accumulated in the plants on organic soil in both years than on mineral soil. Nitrogen accumulation was almost double in 'Fontana' roots in 2004 than in 2003 on organic soil without N applied, but this did not occur on mineral soil.

On mineral soil in 2002, more N was applied than was removed in the harvested portion of the root at the recommended application rate (Table 3.1). A notable amount of N remained in the tops at harvest. No attempt was made to quantify the N remaining in the fibrous roots at harvest, since the N contained in the fibrous roots would be quickly available to the following crop. In 2003, there was a positive net removal in the no N treatment and net removal declined as N rate increased. At the rate necessary to maximize yield (200% of recommended – data shown in Chapter 2), a negative net removal occurred (Table 3.1). Only the N content in 'Fontana' roots significantly increased with increasing N rate. The trend in 2004 was similar to the 2003 results (Table 3.1). The N rate necessary to maximize yield (recommended N rate – data shown in Chapter 2) resulted in a net loss of N over the season. There were no major differences between the cultivars in any of the three years on mineral soil (Table 3.1). Overall, N uptake and removal were low on mineral soil, which was mainly due to low DM production on mineral soil, especially in 2003 and 2004, and less available water. Nitrogen use efficiency at the N application rate that maximized yield (Chapter 2) could not be calculated in 2002 (no N applied), and averaged 20.9 and 51.8 kg DM·kg N applied^{-1} for 2003 and 2004, respectively (data not shown). Fertilizer N recovery at the N

Table 3.1. Nitrogen (N) budget as affected by N application rate of two carrot cultivars grown on mineral soil.

Year	N Application Rate	N Applied ($kg \cdot ha^{-1}$)		N in Tops ($kg \cdot ha^{-1}$)		N in Roots ($kg \cdot ha^{-1}$)		Total N Uptake ($kg \cdot ha^{-1}$)		Net N Removal[z] ($kg \cdot ha^{-1}$)	
		Rainfall	Fertilizer	Idaho	Fontana	Idaho	Fontana	Idaho	Fontana	Idaho	Fontana
2002	100	8.0	110	24.9	32.8	81.1	72.2	106.1	105.0	-36.9	-45.8
2003	0	8.0	0	18.4	19.4	35.0	34.7	53.4	54.1	27.0	26.7
	100	8.0	110	29.5	30.9	70.2	44.1	99.7	75.0	-47.8	-73.9
	200	8.0	220	60.3	26.8	135.5	70.7	195.8	97.5	-92.5	-157.3
Significance	L	--	--	NS	NS	NS	*	NS	NS	NS	***
	Q	--	--	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	0.58	--	--	--	0.97
2004	0	8.0	0	18.8	15.2	34.0	32.4	52.8	47.6	26.0	24.4
	50	8.0	55	29.8	26.5	67.9	55.4	97.7	81.9	4.9	-7.6
	100	8.0	110	35.0	21.1	80.2	49.1	115.2	70.2	-37.8	-68.9
	150	8.0	165	39.5	51.2	80.6	162.7	120.1	213.9	-92.4	-10.3
	200	8.0	220	47.6	20.1	93.9	76.7	141.5	96.8	-134.1	-151.3
Significance	L	--	--	**	NS	NS	NS	*	NS	***	**
	Q	--	--	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	0.37	--	--	--	0.29	--	0.75	0.39

[z] Net N removal = N in roots – N applied.

application rate that maximized yield could not be calculated in 2002, and averaged 31.2 and 28.6% for 2003 and 2004, respectively (data not shown). Fertilizer N recovery ranged from 8.5 to 79% at all N application rates.

On organic soil, N uptake and removal were much higher than on mineral soil (Table 3.2). Total N uptake in the shoot and storage root was up to 380 $kg \cdot ha^{-1}$ over the growing season. This resulted in a net removal of N at all N application rates in all years. Net removal was higher for 'Fontana' than for 'Idaho' in 2002 and 2004, but not in 2003. The highest net removal was 282 $kg \cdot ha^{-1}$ N at the no N application rate. Overall, N application rate did not affect the uptake of N or the accumulation in the tops and roots (Table 3.2). Up to 80 $kg \cdot ha^{-1}$ N was returned to the soil in the tops (Table 3.2). Since no N was required for maximum yield in all three years (Chapter 2), NUE and FNR for the optimum N application rate could not be calculated for organic soil because no N was applied (data not shown). However, FNR values ranged from 0 to 47% at all N application rates.

3.4 Discussion

3.4.1 Accumulation and Partitioning of DM and N Over the Season

The results revealed that both DM and total N accumulation follow similar patterns. Dry matter and N content in the roots were low at 53-67 DAS, and it can be suggested that there is a small and gradual increase in both DM and N content in the roots until about 50 DAS. Between 50 and 60 DAS, DM and total N must begin to accumulate at a rapid rate (40-140 $kg \cdot ha^{-1} \cdot d^{-1}$ DM; 0.4-3.3 $kg \cdot ha^{-1} \cdot d^{-1}$ N). It is important to note that the period of rapid increase was not constant among years or soil types. The period of rapid increase was about 10 days earlier on average (50 DAS) in 2003 than in 2004. The

Table 3.2. Nitrogen (N) budget as affected by N application rate of two carrot cultivars grown on organic soil.

Year	N Application Rate	N Applied (kg·ha^{-1})		N in Tops (kg·ha^{-1})		N in Roots (kg·ha^{-1})		Total N Uptake (kg·ha^{-1})		Net N Removal[z] (kg·ha^{-1})	
		Rainfall	Fertilizer	Idaho	Fontana	Idaho	Fontana	Idaho	Fontana	Idaho	Fontana
2002	100	8	60	71.1	58.8	167.3	192.3	238.4	251.1	99.3	124.3
2003	0	8	0	78.7	57.7	137.7	142.6	216.4	200.3	129.7	134.6
	100	8	60	79.1	51.7	147.7	133.1	226.8	184.8	79.7	65.1
	200	8	120	79.2	56.7	194.1	144.9	273.3	201.6	66.1	16.9
Significance	L	--	--	NS	NS	NS	NS	NS	NS	NS	**
	Q	--	--	NS	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--	--	--	--	0.77
2004	0	8	0	55.6	42.0	175.9	290.3	231.5	332.3	167.9	282.3
	50	8	30	46.5	50.9	150.4	236.6	196.9	287.5	112.4	198.8
	100	8	60	50.0	54.4	157.8	254.4	207.8	308.8	89.8	186.4
	150	8	90	62.4	41.1	145.9	247.6	208.3	288.7	47.9	149.6
	200	8	120	79.7	63.2	181.0	317.1	260.7	380.3	53.0	189.1
Significance	L	--	--	**	NS	NS	NS	NS	NS	***	NS
	Q	--	--	*	NS	NS	NS	NS	NS	NS	NS
	R^2	--	--	0.47	--	--	--	--	--	0.59	--

[z] Net N removal = N in roots – N applied.

air temperatures were higher in June and July of 2003 than in 2004, and the plots were seeded 10 days later in 2003 on both soil types, at a time when air temperatures were warmer. Thus, it appears that air temperatures, or soil temperatures inferred by air temperatures, play an important role in determining the date of the initiation of storage root growth. This is similar to previous research showing a rapid increase in carrot root fresh weight at 50 DAS (Rubatzky et al., 1999). It is unclear whether there is a physiological or a morphological explanation for this sudden increase in storage root growth. No defined growth stages for carrots have been identified (Strandberg, 2001). However, the initiation of the secondary cambium which produces storage tissue, occurs at the time of true leaf emergence (Esau, 1940), which corresponds to 20 to 34 DAS based on greenhouse experiments (Hole et al., 1987a; Hole and Dearman, 1991). The discrepancy between the initiation of the storage root and the results of this study could be due to slower growth in the field compared to the greenhouse. It is also possible that the rapid increase in DM occurs much later than the initiation of the storage tissue. Hole et al. (1987b) showed that cell number increases exponentially between 34 and 55 DAS and then increases linearly thereafter. In addition, cell number is more closely related to root weight than cell size (Hole et al., 1987b). Furthermore, (Hole et al., 1983) showed a rapid increase in both root and shoot DM between 50 and 75 DAS, and suggested that storage root initiation occurs much earlier than growth curves suggest. Field studies in New York and New Zealand, revealed a rapid increase in both root and shoot DM beginning at 60 to 68 DAS (Platenius, 1934; Reid and English, 2000). The later date of rapid increase in root DM in these studies could be due to reduced photoperiod and cooler air temperatures early in those studies, since carrots were seeded one month earlier

in the New York study than in the current study and were seeded in late winter in the New Zealand study. Since this same period appears to correspond with canopy closure, it is also possible that increased competition among plants in this study may have triggered filling of the storage root or that canopy closure provides a good indication of maximum DM production.

Beyond 60 DAS there was generally a rapid linear increase in both DM and total N content. In some cases there appeared to be a levelling off near harvest, likely due to lower air temperatures, shorter photoperiod, and cloudier conditions prior to harvest at the end of October. It could also be due to allocation of photoassimilates to the tops because of re-growth that occurred after severe leaf blight damage. The slight decline in DM content observed near harvest in a few cases might be due more to anomalous samples rather than redistribution or loss of DM.

In a study conducted in Finland it was shown that between 28 and 41% of carrot root dry weight accumulates during the final month before harvest in a four month growing season, which demonstrates that carrot storage root growth is substantial late in the season (Evers, 1988). In the current study, conducted over a five-month growing season, 15 to 30% of DM accumulated in the final month of the growing season, which would have occurred with reduced photoperiod and air temperatures compared to the final month of the Finland study.

Top growth and N accumulation appeared to increase gradually during the first 50 DAS and reached a maximum near 100 DAS. If a period of rapid increase in DM and N accumulation occurs for top growth, it would have to occur near 25-30 DAS. No samples were collected between seeding and 53 DAS to determine the trends during this period. A

slight decline in both DM and total N content occurred beyond 100 DAS. This decline could be due to decomposition of older leaves at this stage. The results of this study suggest an earlier increase in top growth than previous research that showed a rapid increase in leaf fresh weight beginning 45 DAS (Rubatzky et al., 1999) and a rapid increase in leaf dry weight between 50 and 75 DAS (Platenius, 1934; Hole et al., 1983; Reid and English, 2000). Leaf area increases very slowly until about 50 DAS and then rapidly increases until 100 DAS under sub-tropical conditions in Florida, and leaf area and top dry weight are highly correlated (Strandberg, 2001). The slower development in that study could also be due to a shorter photoperiod, since carrots are grown over the winter in Florida. Top re-growth could explain the slight increase in DM and N content prior to harvest. It is possible that some DM and N were redistributed to the storage roots over the last 50 days of the season in response to colder air and soil temperatures. The decrease beyond 100 DAS was more consistent for N, and previous studies have shown a similar trend for other root crops such as sugarbeet (Armstrong et al., 1986) and chicory (Améziane et al., 1997). This response has been shown to be more pronounced under N-deficient conditions, a result that was not observed in this study. This study confirms an early study by Platenius (1934), which showed that DM content of the tops decreases beyond 105 DAS. The reduction in top DM in that study was attributed to transport of sugars from the top to the root.

Previous reports have shown a more gradual increase in N uptake beginning at around 30 DAS, but also continuing at a linear rate until harvest (Salo, 1999). This more gradual uptake was on a whole plant basis. The current study shows that N accumulation in the tops took priority before 53 DAS and root growth increased sharply beyond 53

DAS. Combining the findings from both studies, it is likely that little N is taken up prior to 30 DAS, the majority of N taken up between 30 and 50 DAS is partitioned to the tops, and most of the N taken up over the growing season is taken up after 50 DAS and is partitioned to the storage root. Since DM production in the tops must begin to rapidly increase later, N uptake and accumulation in the tops in proportion to DM production must be very high near 30 DAS.

Although there was a significant effect of applied N on yield in both years on mineral soil (Chapter 2), there were no differences in the patterns of N uptake or distribution in the tops and roots when carrots were grown with no applied N or the recommended N rate. Consequently, there is no evidence to suggest that carrots distribute more N or DM to the storage root when N availability is in the range experienced in agricultural soils. The two cultivars also showed similar patterns of N and DM accumulation. 'Idaho' is less susceptible to leaf blight than 'Fontana' (Chapter 4), and leaf blight affects the carrots between 50 and 150 DAS. During this period there were no significant differences in total N concentration between the cultivars on either soil type (data not shown). There were also no differences in the patterns of DM accumulation among cultivars early in the season in previous research (Hole et al., 1983; Hole et al., 1987a). As a result, the hypothesis that carrot cultivars that are more susceptible to leaf blight partition less N to the leaves during the time of pathogen infection and development is not supported by these results.

3.4.2. Nitrogen Budget and Potential Use of Carrots as an N Catch Crop

There was substantially less N taken up by the crop and removed in the harvested portion of carrots grown on mineral soil than on organic soil. This resulted in a net addition of N to the soil over the growing season, which would then be available for loss due to leaching or immobilization into soil organic matter. This was especially true when optimal yields occurred at or above the recommended N rate in 2003 and 2004. Similar results were also shown for mineral soil in Michigan (Warncke, 1996). However, in the first year of the current study, although no assessments were made on the no N treatment, there were no differences in yield among the N rates tested, and it is likely that the carrots in the no N treatment would have taken up and removed similar amounts of N as the recommended N rate treatment. This would have resulted in a net removal of N of between 72 and 81 $kg \cdot ha^{-1}$. Earlier reports have shown that carrots can take up nearly 100 $kg \cdot ha^{-1}$ N (Salo, 1999) and 119 $kg \cdot ha^{-1}$ N (Warncke, 1996) from unfertilized plots on mineral soil, and these results confirm that finding. However, in the latter two years when soil residual N throughout the soil profile would have been depleted, only around 50 $kg \cdot ha^{-1}$ N was taken up in unfertilized plots. It is important to note that no irrigation was available on the mineral soil site and this could have restricted yield and N uptake in all years. Total N uptake and removal could have been substantially higher if adequate soil moisture was present throughout the growing season. Overall, carrots have potential as an N catch crop for mineral soils when residual N is available from a preceding crop or yields are maintained at a maximum through optimum irrigation. A catch crop would not be necessary if soil residual N is low. It is likely that carrots in rotation with a crop with a high N requirement such as cole crops could have optimum yields without N application.

In this case, there could be a significant reduction in N losses by including carrots in the rotation. However, leaf blight susceptibility would be high under conditions of low N application (Chapter 4), and would have to be controlled by alternative means.

On organic soil, there is high potential for carrots to be used as an N catch crop. No applied N was required for optimum yield in any of the years of the trial (Chapter 2). In addition, N uptake was not influenced by N application rate. Consequently, in all three years and at all N application rates tested, a large net removal of N occurred. Growing carrots without applied N resulted in a net removal of N from the field of between 130 and 282 $kg \cdot ha^{-1}$ N. Although there was sufficient N in all three years on organic soil (Chapter 2), 'Fontana' took up and removed much more N over the season in 2004 than 'Idaho' carrots, but there were no differences in the other two years. This result suggests that 'Fontana' carrots are capable of taking up and accumulating much more N in the roots than is required for optimum growth, a result that was not observed for 'Idaho'.

Total N uptake by carrots was up to 380.3 $kg \cdot ha^{-1}$ N and averaged 250 $kg \cdot ha^{-1}$ N on organic soil, which is higher than previous reported maximums of 150 $kg \cdot ha^{-1}$ N on mineral soil in Finland (Salo, 1999), 250 $kg \cdot ha^{-1}$ N under very high fertilization (200 $kg \cdot ha^{-1}$ N) on mineral soil in Germany (Rühlmann and Geyer, 1993), 221 $kg \cdot ha^{-1}$ N on mineral soil in Germany (Fink and Scharpf, 2000), 178 $kg \cdot ha^{-1}$ N on mineral soil in Michigan (Warncke, 1996), and 214 $kg \cdot ha^{-1}$ N on organic soil in Quebec (Hamilton and Bernier, 1975). This amount of uptake is also similar to previous reported maximums for cabbage (250-415 $kg \cdot ha^{-1}$ N), broccoli (401 $kg \cdot ha^{-1}$), and cauliflower (254 $kg \cdot ha^{-1}$), which are crops known for their high N requirements and total N uptake over the season (Salo, 1999; Fink and Scharpf, 2000; Westerveld, 2002; Bakker, 2005). The source for the

additional N must be mineralization of soil organic matter or N from deep in the soil profile. Since other crops grown on organic soil such as onion (110 kg·ha^{-1} N), celery (160 kg·ha^{-1} N), and lettuce (89-96 kg·ha^{-1} N) are not capable of the same level of N uptake (Hamilton and Bernier, 1975; Salo, 1999; Fink and Scharpf, 2000), it is likely that at least some of the N released by mineralization is not used by these crops. Consequently, carrots are essential to an organic soil crop rotation since they may reduce N losses substantially more than other crops grown at present on organic soils, even if losses still occur from a carrot crop. Overall, carrots can be used as an N catch crop to remove excess N from organic soil.

Nitrogen remaining in the tops at harvest ranged from a minimum of 15.2 kg·ha^{-1} on mineral soil to a maximum of 79.7 kg·ha^{-1} on organic soil. It is likely that a similar amount of N could be present in the fibrous root system. It was shown in Chapter 2 that there is slightly more DM in the fibrous root system than in the tops, but the N content of the roots would likely be less. This N would be added back to the soil and part would be available to the following crop.

3.4.3. Nitrogen Use Efficiency

Carrots exhibited high NUE based on applied N, since no N was required to produce maximum yield in four of six plots. For the other two plots, there are no published values of NUE to compare the results to. Fertilizer N recovery in the harvested portion was generally low when N was applied on organic and mineral soil, and N application would be required for optimum leaf blight control (Chapter 4). The large N uptake values for carrots, especially on organic soil, suggest that carrots do not exhibit high NUE on an N uptake basis. Therefore, the requirement for little N for optimal yield

is likely due to uptake of N that is not accounted for in the calculation of NUE used in this thesis. This N must be from mineralization of organic matter or residual N from previous seasons.

3.5 Conclusions

The patterns of N and DM accumulation during the growing season are consistent over cultivar, soil type, and N availability. Consequently, the patterns of N partitioning over the season provide no explanation for differences in leaf blight susceptibility between cultivars or treatments. Differences in air temperature among years alter the timing of the period of exponential increase in storage root growth and N accumulation. The majority of N is taken up between 50-60 DAS (mid- to late-July) and harvest. Carrots are capable of taking up and removing much more N than is applied for optimal yield on organic soil and can be used as an N catch crop to remove excess N from the soil and reduce losses. On mineral soil, there is potential for carrots to be used as an N catch crop if there is significant residual N from a previous crop. More N is required than is removed from the field when soil N availability is low. On both soil types N remaining in the tops at harvest could be an important source of N to the following crop. Carrots exhibit high NUE based on N applied, but this is likely due to uptake of mineralized or residual N that is not accounted for in the calculation.

Chapter 4. Nitrogen Nutrition of Carrots in Relation to Alternaria and Cercospora Leaf Blight

Abstract:

Alternaria leaf blight (ALB) and Cercospora leaf blight (CLB) are economically important diseases of carrots in Ontario, and are typically managed with the application of 6 to 12 fungicide sprays in a growing season. Field and greenhouse experiments were conducted to determine the effect of N management on both diseases and on two carrot cultivars, 'Idaho' and 'Fontana', that differ in susceptibility to the diseases. Five N rates ranging from 0 to 200% of current Ontario recommended N rates were applied on organic and mineral soil from 2002 to 2004. Both diseases were rated biweekly on a scale of 0 to 10 (0-no symptoms; 10-canopies destroyed), the number of lesions per leaf was counted in mid-September. Sap NO_3-N concentrations were determined throughout the season, and canopy health was assessed at harvest. Cultivars were compared to determine the relationship between the NO_3-N status of the plants and disease severity. Foliar N application was assessed on both soil types as an alternative means of reducing disease severity. Three N rates were applied to carrots grown in the greenhouse in silica sand and soilless mix, and conidial suspensions of both pathogens were applied to the plants using an airbrush or fine-mist sprayer. Disease severity, senescence, and sap NO_3-N concentration were assessed before and during symptom development. Both area under the disease progress curve and the number of lesions per leaf in mid-September consistently increased with decreasing N rate for both diseases. This resulted in fewer live leaves per plant at harvest in low N treatments, which would result in reduced ability

to mechanically harvest the crop. There were no consistent differences in the response of ALB or CLB to N application rate among cultivars, soil types, and years.

Foliar N application did not provide consistent control of either disease. Alternaria leaf blight severity increased with increasing leaf senescence. Although disease severity of a single cultivar was consistently increased with decreasing NO_3-N status of the plants, differences in NO_3-N status between the cultivars had no relationship to disease susceptibility.

4.1 Introduction

Alternaria leaf blight (ALB), caused by *Alternaria dauci* (Kühn) Groves and Skolko and Cercospora leaf blight (CLB) caused by *Cercospora carotae* (Passerini) Solheim are important destructive diseases of carrots in Ontario. Alternaria leaf blight symptoms usually appear in early August in the province and continue until harvest. The disease predominates on older and senescing leaves (Soteros, 1979; Rotem, 1994). Cercospora leaf blight symptoms typically appear in early July and continue until harvest. The disease can occur anywhere on the carrot foliage but is usually most severe on younger leaves. Both diseases begin on leaflets and can spread to petioles. Severe infections of either disease can lead to leaf senescence and necrosis and a general weakening of the foliage, which can lead to tops breaking off during mechanical harvest leaving many carrots unharvested (Langenberg, 1975).

Alternaria leaf blight is decreased by nitrogen (N), phosphorus (P), and potassium (K) fertilizers in Israel (Vintal et al., 1999) and Florida (White et al., 1983). The interaction between N application rate and ALB severity could be due to delayed leaf

senescence and delayed infection (Vintal et al., 1999). In addition, the ALB and CLB complex is decreased by N fertilizer application in Michigan (Warncke, 1996) and Ontario (Westerveld et al., 2002). Cercospora leaf blight increases with increasing N concentration of the nutrient solution in the greenhouse (Thomas, 1943), but there is no relationship between CLB severity and leaf N concentration in the field (Tremblay and Charbonneau, 1993). No studies have examined the effects of N application rate alone on ALB and CLB separately in the field.

The potential interactions between N nutrition of the carrot crop and the severity of ALB and CLB could complicate N and disease management of the crop. Research is required to assess the potential interaction between N application rate and disease severity for each disease separately, and to identify potential causes for the observed effects. In addition, the relationship between N and the susceptibility of cultivars to ALB and CLB needs to be investigated. The literature has led to the following hypothesis, which was tested in the field and greenhouse by comparing disease severity under different N application rates and methods and by comparing disease severity to the N status of the plant and leaf senescence:

1. The ALB susceptibility of different carrot cultivars and carrots grown at varying N application rates is influenced by the status of N in the host plant and the effects of N on leaf senescence, whereas that of CLB is not.

4.2 Materials and Methods

4.2.1 Nitrogen Rate in the Field

Nitrogen rate experiments were established as described in Chapter 2. Cultivars with differing susceptibility to leaf blight, 'Idaho' (semi-susceptible) and 'Fontana' (highly susceptible) were used in all field experiments. Assessments of leaf blight in this study were done within the half of each plot that received the same rate of N for all three years (annual fertilizer section). Preplant available N was calculated as described in Chapter 2.

Once leaf blight symptoms were first observed, visual ratings on all treatments and cultivars of each disease were done biweekly using a scale of 0 to 10 (0 - no symptoms, 1 - <10 lesions on leaves, 2 - some lesions mainly on leaves, 3 – moderate number of lesions mainly on leaves, 4 - many lesions on leaves and some on petioles, 5 – numerous lesions on leaves and moderate number on petioles, 6 - numerous lesions on leaves and petioles, 7 –25% of leaves destroyed, 8 – 50% of leaves destroyed, 9 – 75% of leaves destroyed, and 10 – 100% of leaves destroyed). Area under the disease progress curve (AUDPC) was calculated for each treatment. On 23 Sept. (2003) and 13 Sept. (2004) on organic soil, and 18 Sept. (2003) and 17 Sept. (2004) on mineral soil, the number of lesions per leaf of both ALB and CLB were counted on each leaf of three plants as a more accurate indication of leaf blight severity and to test the accuracy of the rating system. At harvest, the number of live leaves on 10 carrots per treatment, replication, and cultivar were recorded. No fungicides were applied for leaf blight control in 2002 on either soil type. Due to disease pressure, a fungicide program was required in 2003 and 2004. In 2003, fungicide Bravo (chlorothalonil) was applied at a rate of 3.0

$L \cdot ha^{-1}$ to the organic soil plot on 18 Aug. In 2004, the fungicide Lance (boscalid) at 315 $g \cdot ha^{-1}$ was sprayed on 6 Aug and 23 Aug on the organic soil plots and 9 Aug and 23 Aug on the mineral soil plots.

For comparisons between disease severity and sap NO_3-N concentrations, tissue samples were collected and analysed for NO_3-N concentration using the Cardy nitrate meter as described in Chapter 2. The mean of sap NO_3-N concentration each year was compared to season-long AUDPC data for each cultivar, soil type, and year using linear correlation analysis. The number of lesions per leaf in mid-September was compared with the final sap NO_3-N concentration in 2003 and 2004 using linear correlation analysis.

4.2.2 Foliar Nitrogen

Foliar N experiments were established as described in Chapter 2. Leaf blight was rated as described for the N rate experiments above, as well, a count of the number of lesions per leaf in mid-September in 2003 and 2004 was taken on the no N control treatment and the no N preplant plus foliar spray with surfactant treatment only, using three of the four replications only due to time constraints. Weather conditions for all plots were summarized in Table 2.1.

4.2.3 Cultivar vs. Leaf Blight Assessment

To determine the relationship between leaf blight susceptibility of cultivars and petiole sap NO_3-N content, leaf blight severity was rated using the above system on four cultivars from each of two cultivar evaluation trials established at the University of

Guelph, Muck Crops Research Station on 1 Oct. in 2004. Both trials were established as described above for the other field experiments but were seeded using a push V-belt seeder. The cultivars assessed in the first trial were orange carrot cultivars 'Bradford', 'Fontana', 'Svr 712222', and 'Sunrise'. The carrots grown in the second trial were various coloured carrot breeding lines (Phil Simon, University of Wisconsin, Madison) W 104-3 (Red), W 106-3 (Purple), W 101-23 (Dark Orange), and the cultivar 'Cellobunch'. Both trials received a regular fungicide spray program for leaf blight control. Nitrate analysis was as described for the N rate experiment, but three groups of four petioles were assessed for each experimental unit.

4.2.4 Nitrogen Rate and ALB and CLB severity in the Greenhouse

Alternaria dauci

Trials to determine the effect of N rate on infection of carrots by *A. dauci* 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 98% pure silica sand at 8-10 seeds per pot, thinned to three plants per pot after emergence. Pots were drip irrigated with tap water daily. Following germination, a 50% Hoagland solution lacking N, as described by Hoagland and Arnon (1938) was prepared with well water and pots were flooded by hand with 500 mL of the solution biweekly. Treatments consisted of three N rates applied during each hand watering. The three N rates consisted of ammonium nitrate added at a rate of 50%, 100%, and 200% of the N required for a 50% Hoagland solution. There were eight pots per treatment/cultivar combination; one pot for *A. dauci* inoculation, one pot for water inoculation as a control, and four replications. Prior to fungal inoculation, four

recently mature petioles were collected from each treatment/cultivar and tested for NO_3-N content using a Horiba 'Cardy' Model C-141 nitrate meter.

Inoculation

Local isolates of *A. dauci* could not be obtained because cultures were consistently contaminated with *A. alternata*. Consequently, *Alternaria dauci* cultures were obtained from an isolate collected from the field at the Mid-Florida Research and Education Center in Apopka, Florida (courtesy of J. Strandberg). The isolate was recultured several times on carrot leaf agar (CLA) following the procedures described by Strandberg (1987) before being used to inoculate the carrots. Plates were placed under fluorescent grow lights (30 W GE Bright Stik Gro and Sho; 470 lumens) with 18-hour day length and a temperature between 21 and 26^{o}C. When greenhouse carrots were at the 10-leaf stage, cultures were flooded with a 0.01% Tween 80 (v/v) solution prepared using sterilized distilled water as described by Carisse and Kushalappa (1990) and conidia were loosened using a glass rod. The suspension obtained was passed through a 100-mesh sieve and adjusted to a spore concentration of 10,000 spores·mL^{-1} using a haemocytometer. A mid-aged leaf from each pot was sprayed with conidial solution using a Badger-350 artist airbrush according to the procedures described by Carisse and Kushalappa (1990). A single leaf was chosen rather than whole plants due to low spore production by the *A. dauci* cultures and low volume of conidial suspension as a result. The conidial suspension was used immediately after preparation. The inoculated leaves were rated for senescence prior to inoculation using a scale of 0 to 10: 0 = dark green, 1 = moderately green, 2 = light green, 3 = mild chlorosis on old leaves only, 4 = mild

chlorosis on most leaves, 5 = moderate chlorosis on most leaves, 6 = major chlorosis on most leaves, 7 = some necrosis of old leaves, 8 = partial necrosis of most leaves, 9 = moderate necrosis of most leaves, 10 = complete necrosis of all leaves. Three water agar plates were sprayed with the conidial suspension before, during, and after plant inoculation to determine the percent spore germination. The plates were placed in the dark and assessed after three days. Half of the pots in the greenhouse were sprayed with 0.01% Tween 80 solution lacking spores as a non-inoculated control. Leaves sprayed with conidial suspension or Tween 80 solution were covered with plastic bags for two days to maintain leaf wetness and promote infection. After 12 and 21 days the number of ALB lesions on each sprayed leaf was counted.

Cercospora carotae

In fall 2004 and winter 2005, carrots were grown as described above for *A. dauci* inoculation, but were irrigated with well water using ebb and flow benches. The nutrients were applied in the irrigation water at a rate equal to a 25% Hoagland solution lacking N, and pots were irrigated every two days (every day without nutrients until seedling emergence). Nitrogen rates were as described for ALB. Prior to fungal inoculation, four recently mature petioles were collected from each treatment/cultivar and tested for NO_3-N content using a Horiba 'Cardy' Model C-141 nitrate meter. Prior to inoculation and six weeks after inoculation (AI) plants were rated for senescence using the scale described for the Alternaria experiment, but applying the scale to the average leaf of the whole top.

Inoculation

Cercospora carotae isolates were obtained from field experiments at the University of Guelph, Muck Crops Research Station in the fall of 2004 from plants that received no foliar fungicides. Isolates were cultured on carrot leaf agar (CLA) following the procedures described by Strandberg (1987). The original isolates were re-cultured once prior to the experiment. Cultures were placed under fluorescent grow lights (30 W GE Bright Stik Gro and Sho; 470 lumens) with 12-hour light and dark periods and maintained at a temperature between 21 and 26^{o}C. Conidia were produced after two months. When greenhouse carrots were at the 6-7 leaf stage, cultures were flooded and a conidial suspension was obtained using the same procedures as described for *A. dauci* inoculation above. Entire plants were sprayed with conidial suspension using a Badger-350 artist airbrush. Percent spore germination was determined using the methods described for *A. dauci* except the growth medium was potato dextrose agar. The plates were placed in the dark and assessed after three days. Eight additional pots in the low N treatment were sprayed with 0.01% Tween 80 solution as the non-inoculated control. Plants were covered with plastic bags for 7 days to maintain leaf wetness and promote infection. After 4 and 6 weeks, the number of CLB lesions per leaf was counted within each pot. Following the final leaf blight assessment, two leaves were collected from each pot and assessed for NO_3-N concentration using the nitrate meter described above. The number of CLB lesions was counted on each of the two leaves prior to NO_3-N assessment.

The CLB experiment was repeated using pots filled with Sunshine 2 growing mix that lacked added nutrients, and carrots were inoculated with *C. carotae* as described

above. The soilless mix was used because it more closely matched the high organic matter content and water and nutrient availability of organic soil and ensured more normal carrot growth. A fine mist hand sprayer was used instead of the artist airbrush to inoculate plants because it provided a thicker coverage of plant material, increased leaf wetness, and the airbrush canister would repeatedly freeze after prolonged use, preventing even coverage of the plants.

These trials had severe aphid infestations during the early growth phase and these were controlled using a single spray of Assail 70 Wp (acetamiprid 70%) at a rate of 124 $mg \cdot L^{-1}$ of water. A severe powdery mildew outbreak occurred during the period between inoculation with *C. carotae* and symptom development. Relative humidity was very high because of cloudy/rainy weather during this time, which promoted the disease. Plants were sprayed daily with tap water to deter powdery mildew, since infections are more severe on dry leaves.

4.2.5 Statistical Analysis

Field experiments were arranged in a split-block design with cultivar as the main plot, N rate as the sub-plot, and four replications. Greenhouse experiments were arranged as a randomized complete block design. The fit of five analytical models for disease progression over the growing season was analysed using EPIMODEL according to the procedures described by Nutter and Parker (1997). The equations assessed were: Monomolecular $y=1-(1-y_0)\exp(-r_M t)$, Exponential $y=(y_0)\exp(r_E t)$, Logistic $y=1/(1+[(1-y_0)/y_0]\exp(-r_L t))$, Gompertz $y=\exp([\ln(y_0)]\exp(-r_G t))$, and Linear $y=b_0+b_1 t$. An analysis of variance was performed on each data set to partition the variance into treatment, block, cultivar, soil type, and year effects, where applicable, and to identify interactions among

these effects. Data from the N rate treatments in the field and the greenhouse were analysed by linear and quadratic regression analysis. The entire data set for each assessment was assessed for normality using the Shapiro-Wilk test of residuals. Outliers were identified using Lund's test of standardized residuals (Lund, 1975). Linear correlation analysis was performed for comparison among dependent variables. Data were analyzed using the PROC GLM, PROC CORR, PROC PLOT, and PROC Univariate procedures of SAS version 8.0 (SAS Institute, Cary NC) and the linear models sections of Statistix V.4.1. Significant regression equations from Chapter 4 are listed in Appendix 4.

4.3 Results

4.3.1 Nitrogen Rate in the Field

The severity of ALB and CLB, as indicated by AUDPC, decreased with increasing N rate on both mineral and organic soil, except in 2002 on mineral soil where no relationship between N rate and AUDPC was observed (Table 4.1). Leaf blight was more severe on 'Fontana' than 'Idaho' carrots (Appendix 5), but the response of ALB and CLB to N was consistent for both cultivars and combined results are reported for all field data. The poorest relationships between N rate and AUDPC occurred on mineral soil in 2002 and on organic soil in 2004. In 2002 on mineral soil, low rainfall and an inability to irrigate the plots resulted in some wilted areas within the plot and an increase in leaf blight severity within those areas. In 2004 on organic soil, leaf blight was severe throughout the season even after three fungicide applications. Cercospora leaf blight began on the cotyledons in spring, which was mostly due to volunteer carrots from the previous year that were infested with the disease. This shows the benefits of crop

Table 4.1. Effect of nitrogen (N) application rate on Alternaria and Cercospora leaf blight area under the disease progress curve (AUDPC) for carrots grown on mineral and organic soil on the same location for three consecutive years. Nitrogen was applied in each of the three years.

Soil	N rate[z]	Alternaria AUDPC			Cercospora AUDPC		
		2002	2003	2004	2002	2003	2004
Organic	0	332.9	388.6	432.2	427.6	410.0	398.8[y]
	50	310.4	378.1	397.3	415.5	409.9	367.8
	100	278.0	348.4	374.6	384.3	398.4	367.3
	150	279.2	335.8	353.5	381.6	373.3	344.5
	200	279.8	336.0	359.5	375.3	373.6	311.5
Significance	L	***	***	***	***	**	***
	Q	*	NS	*	NS	NS	NS
	R^2	0.41	0.54	0.69	0.63	0.46	0.62
Mineral	0	212.3	378.2	416.8	187.0	384.6	369.3
	50	221.3	369.9	402.5	202.8	374.4	374.5
	100	211.9	334.0	357.5	191.8	334.6	316.3
	150	182.9	331.9	338.8	171.6	307.0	322.9
	200	187.7	306.2	331.1	189.4	297.9	276.1
Significance	L	NS	***	***	NS	***	**
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	0.57	0.50	--	0.66	0.34

[z] Percent of recommended. Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Cultivars could not be combined: 'Idaho' data reported only; 'Fontana' statistics: L=***, Q=NS, R^2=0.47.

NS,*,**,*** Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

rotation. Because of the severity of the disease, only minor differences were observed among treatments. It is likely that the disease quickly overcame the minor resistance provided by adequate N fertility in this plot.

There were no relationships between preplant available N in the top 30, 60, or 90 cm of soil and ALB or CLB severity on mineral soil. On organic soil, there was a significant negative linear relationship between preplant available N in the top 30 (R^2=0.74), 60 (R^2=0.77), and 90 cm (R^2=0.75) of soil and ALB AUDPC, and between preplant available N in the top 30 (R^2=0.63), 60 (R^2=0.62), and 90 cm (R^2=0.61) of soil and CLB AUDPC. This was comparable to the negative linear relationship between N application rate and ALB (R^2=0.74) and CLB (R^2=0.68) for the three rates and three replications used for this analysis.

The Gompertz and Linear models best described disease progression over the season for both diseases, cultivars, and soil types, but the linear model was better than the Gompertz model on organic soil (Table 4.2). Only results for these two models are presented. There were no consistent effects of N application rate on the fit of the model or the slope of the disease progress curve. Both models fitted the mineral soil data better than for organic soil.

The number of Alternaria and Cercospora lesions per leaf decreased with increasing N rate in all cases except for CLB on organic soil in 2004 (Table 4.3). The weakest relationship between N rate and lesions per leaf occurred on mineral soil in 2004, which was likely due to other diseases such as aster yellows and bacterial soft rot in the mineral soil plot. ‘Idaho’ carrots had fewer ALB and CLB lesions per leaf than ‘Fontana’ carrots in all cases (Appendix 5).

Table 4.2. Comparison of two analytical models of disease progression for Alternaria (ALB) and Cercospora (CLB) leaf blight on two carrot cultivars grown at five nitrogen (N) application rates on mineral and organic soils.

N Rate	Cultivar	Disease	Gompertz Model			Linear Model		
			Intercept	Slope	R^2	Intercept	Slope	R^2
Mineral Soil								
0	Fontana	ALB	-1.739	0.801	0.952	0.110	0.123	0.899
50	Fontana	ALB	-1.721	0.842	0.963	0.125	0.124	0.894
100	Fontana	ALB	-1.781	0.809	0.959	0.095	0.125	0.917
150	Fontana	ALB	-1.878	0.821	0.949	0.060	0.129	0.911
200	Fontana	ALB	-1.913	0.791	0.921	0.057	0.124	0.945
0	Fontana	CLB	-1.403	0.755	0.839	0.162	0.118	0.862
50	Fontana	CLB	-1.479	0.829	0.931	0.175	0.118	0.852
100	Fontana	CLB	-1.476	0.736	0.801	0.124	0.120	0.886
150	Fontana	CLB	-1.593	0.788	0.920	0.142	0.120	0.884
200	Fontana	CLB	-1.791	0.777	0.892	0.088	0.120	0.917
0	Idaho	ALB	-1.559	0.838	0.935	0.142	0.123	0.873
50	Idaho	ALB	-1.618	0.804	0.940	0.133	0.123	0.862
100	Idaho	ALB	-1.666	0.814	0.932	0.065	0.123	0.847
150	Idaho	ALB	-1.477	0.736	0.826	0.115	0.122	0.867
200	Idaho	ALB	-1.652	0.787	0.899	0.113	0.122	0.874
0	Idaho	CLB	-1.614	0.790	0.911	0.132	0.121	0.870
50	Idaho	CLB	-1.544	0.786	0.931	0.163	0.118	0.855
100	Idaho	CLB	-1.588	0.782	0.926	0.148	0.119	0.872
150	Idaho	CLB	-1.690	0.788	0.910	0.116	0.121	0.887
200	Idaho	CLB	-1.692	0.771	0.868	0.104	0.118	0.900
Organic Soil								
0	Fontana	ALB	-0.897	0.300	0.593	0.168	0.056	0.693
50	Fontana	ALB	-0.843	0.288	0.548	0.175	0.054	0.662
100	Fontana	ALB	-0.815	0.431	0.599	0.247	0.077	0.683
150	Fontana	ALB	-0.888	0.429	0.595	0.221	0.078	0.702
200	Fontana	ALB	-0.977	0.468	0.661	0.206	0.084	0.766
0	Fontana	CLB	-1.191	0.406	0.698	0.148	0.064	0.749
50	Fontana	CLB	-0.736	0.490	0.695	0.290	0.080	0.676
100	Fontana	CLB	-0.470	0.445	0.551	0.295	0.079	0.661
150	Fontana	CLB	-0.821	0.479	0.664	0.266	0.080	0.693
200	Fontana	CLB	-0.739	0.495	0.638	0.263	0.082	0.713
0	Idaho	ALB	-1.243	0.590	0.800	0.186	0.087	0.792
50	Idaho	ALB	-0.925	0.423	0.589	0.226	0.076	0.733
100	Idaho	ALB	-1.407	0.513	0.758	0.192	0.079	0.764
150	Idaho	ALB	-1.495	0.515	0.756	0.174	0.080	0.763
200	Idaho	ALB	-1.494	0.523	0.781	0.165	0.082	0.812
0	Idaho	CLB	-0.883	0.536	0.763	0.271	0.083	0.703
50	Idaho	CLB	-0.853	0.507	0.705	0.278	0.080	0.675
100	Idaho	CLB	-1.049	0.545	0.762	0.273	0.080	0.699
150	Idaho	CLB	-1.075	0.534	0.722	0.258	0.080	0.694
200	Idaho	CLB	-0.998	0.459	0.627	0.244	0.077	0.711

Table 4.3. Effect of nitrogen (N) application rate on Alternaria and Cercospora leaf blight lesions per leaf in mid-September for carrots grown on mineral and organic soil on the same location for three consecutive years. Nitrogen was applied in each of the three years.

Soil	N rate[z]	Alternaria Lesions per Leaf		Cercospora Lesions per Leaf	
		2003	2004	2003	2004
Organic	0	4.5	3.0[y]	24.2	41.1
	50	3.8	3.6	21.1	36.5
	100	3.4	2.5	20.1	32.2
	150	3.1	2.2	17.7	39.4
	200	3.2	1.6	14.0	39.2
Significance	L	**	*	***	NS
	Q	NS	NS	NS	NS
	R^2	0.30	0.31	0.70	--
Mineral	0	6.6	9.5	23.5	26.2
	50	7.2	6.0	25.4	26.8
	100	4.2	4.7	22.0	19.3
	150	5.6	5.6	16.7	19.4
	200	3.3	4.0	14.0	14.1
Significance	L	**	*	***	*
	Q	NS	NS	NS	NS
	R^2	0.36	0.14	0.29	0.15

[z] Percent of recommended. Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Treatment by cultivar interaction – cultivars could not be combined – 'Idaho' data reported only. 'Fontana' statistics: L=*, Q=*, R^2=0.39.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

The number of live leaves per plant that survived to harvest increased with increasing N rate, except on mineral soil in 2002 and organic soil in 2004 (Table 4.4). On mineral soil in both 2003 and 2004 there were twice the number of live leaves per plant at harvest at the highest N rate compared to the lowest N rate (Table 4.4). 'Idaho' carrots had more live leaves per plant at harvest than 'Fontana' carrots on organic soil in all three years and on mineral soil in 2002, but there were no differences on mineral soil in 2003 or 2004 (Appendix 5).

In most cases, 'Fontana' carrots had much higher sap NO_3-N concentrations than 'Idaho' carrots at all three sampling dates (Appendix 5). Mean sap NO_3-N concentrations over the season were negatively correlated with season long ALB and CLB AUDPC for both cultivars and soil types in 13 of 16 cases in 2003 and 2004, but only for CLB on 'Fontana' carrots grown on organic soil in 2002 (Table 4.5). The number of ALB lesions per leaf in mid-September was negatively correlated with late-season sap NO_3-N concentrations on both cultivars on organic soil in 2003 (Table 4.6). The number of CLB lesions per leaf in mid-September was negatively correlated with late-season sap NO_3-N concentrations on 'Fontana' carrots on organic soil in 2003 (Table 4.6). In all other cases there were no significant linear correlations between late season lesions per leaf and sap NO_3-N concentrations (Table 4.6).

Crop Observations: 'Fontana' carrots were observed to have a smaller canopy and produced fewer new leaves late in the season than 'Idaho' carrots. Disease levels were higher throughout the season than would occur under optimal chemical disease control. There appeared to be more CLB lesions on younger and mid-aged leaves than on older

Table 4.4. Effect of nitrogen (N) application rate on the number of live leaves per plant at harvest for carrots grown on mineral and organic soil on the same location for three consecutive years. Nitrogen was applied in each of the three years.

Soil	N rate[z]	Number of Live Leaves per Plant		
		2002	2003	2004
Organic	0	3.2	3.9	5.4
	50	4.0	4.4	5.2
	100	3.7	5.0	4.9
	150	4.1	5.1	5.8
	200	3.9	5.1	4.8
Significance	L	**	**	NS
	Q	NS	NS	NS
	R^2	0.23	0.42	--
Mineral	0	2.7	2.0	3.0
	50	2.4	2.5	3.5
	100	3.0	3.2	4.5
	150	3.9	3.5	5.3
	200	3.0	4.0	6.1
Significance	L	NS	***	***
	Q	NS	NS	NS
	R^2	--	0.70	0.66

[z] Percent of recommended. Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.
NS,*,**,*** Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table 4.5. Linear correlation coefficients (r) for the comparison of mean Cardy meter nitrate-N readings over the season to area under the disease progress curve for carrots grown on organic and mineral soil from 2002 to 2004.

Soil Type/Year	Alternaria				Cercospora			
	Idaho		Fontana		Idaho		Fontana	
	P[z]	r	P	r	P	r	P	r
Organic								
2002	0.2833	-0.25	0.4326	-0.19	0.2469	-0.27	0.0142	-0.54
2003	0.0299	-0.49	0.0209	-0.51	0.0368	-0.47	0.2504	-0.27
2004	0.0294	-0.49	0.0241	-0.50	0.0015	-0.66	0.0145	-0.54
Mineral								
2002	0.2381	-0.28	0.2499	-0.27	0.2039	-0.30	0.0569	-0.43
2003	0.0025	-0.64	0.1852	-0.31	0.0178	-0.52	0.0749	-0.41
2004	0.0187	-0.52	0.0188	-0.52	0.0442	-0.45	0.0285	-0.49

[z] P = probability, significant at <0.05.

Table 4.6. Linear correlation coefficients (r) for the comparison of the late-season Cardy meter nitrate-N readings to Alternaria and Cercospora lesions per leaf in mid-September for carrots grown on organic and mineral soil from 2002 to 2004.

Soil Type/Year	Alternaria				Cercospora			
	Idaho		Fontana		Idaho		Fontana	
	P[z]	r	P	r	P	r	P	r
Organic								
2003	0.0092	-0.57	0.0005	-0.70	0.2529	-0.27	0.0191	-0.52
2004	0.0867	-0.39	0.0940	-0.38	0.3397	-0.23	0.4993	0.16
Mineral								
2003	0.5216	-0.15	0.1774	-0.31	0.2090	-0.29	0.1472	-0.34
2004	0.0785	0.40	0.0515	-0.44	0.3259	0.23	0.5825	-0.13

[z] P = probability, significant at <0.05.

leaves, but ALB symptoms on older leaves could have masked the symptoms of CLB. Carrots given higher N application rates appeared to produce more new leaves late in the season than carrots given low N application rates. Alternaria leaf blight symptoms were mainly on mid-aged and older senescing leaves. The main differences observed in disease severity between plants in high N and low N conditions were that plants given high N had fewer lesions on petioles and had fewer leaves with severe infections. There appeared to be more leaf senescence in the low N treatments than can be attributed to disease alone. No significant nutrient deficiencies other than N deficiency were noted on organic soil, but slight deficiencies of P, Mg, Zn, and Mn may have occurred on mineral soil in 2003 and 2004 based on comparison between tissue nutrient concentrations at harvest and published critical values as suggested in Chapter 2. An outbreak of aster yellows and bacterial rot of the leaves occurred on mineral soil late in the season in 2004, and this caused numerous leaf symptoms that resembled P and K deficiencies and may have caused the deficiencies noted in this trial at harvest (Figure 4.1).

Carrots grown with high rates of N in 2004 on mineral soil were not representative of a normal crop canopy due to seedling death and sparse stands (Figure 4.2). The plants that remained had much larger leaves that would have had less opportunity for disease to develop due to improved airflow around the canopy.

The canopies were less healthy each year, and the canopies did not close in the last year of the three-year trial. The weakened canopies in the latter years of the trial were likely due to early season seedling damage, aster yellows and bacterial diseases on both soil types, and a significant number of carrot rust flies that damaged roots on organic soil.

Figure 4.1. Nutrient deficiency symptoms on carrot leaves on mineral soil in 2004 induced by aster yellows.

Figure 4.2. Thin stand of carrots on mineral soil in 2004 influenced by high nitrogen application rates.

4.3.2 Foliar Nitrogen

Foliar applied N decreased ALB severity as indicated by AUDPC in 2004 on organic soil and increased severity in 2002 on mineral soil when compared to the no N treatment (Table 4.7). Cercospora leaf blight severity as indicated by AUDPC was decreased by foliar N application in 2004 on organic soil and in 2003 on mineral soil, but was increased by foliar N on mineral soil in 2004. Foliar sprays of N with surfactant resulted in lower CLB severity than without surfactant on mineral soil in 2003 and on organic soil in 2004. All other differences among the treatments receiving foliar sprays with surfactant can be attributed to differences in preplant N rate (Table 4.7). 'Idaho' carrots had lower ALB and CLB than 'Fontana' carrots in all cases (Appendix 5).

Foliar N application with surfactant decreased the number of Alternaria lesions per leaf in mid-September compared with the no N control in 2003 (Table 4.8). In all other cases there was no effect of foliar N application with surfactant on ALB or CLB lesions per leaf (Table 4.8). 'Idaho' carrots had fewer lesions per leaf of both ALB and CLB than 'Fontana' carrots in all cases (Appendix 5).

On organic soil in 2004, the number of live leaves per plant at harvest was much higher in the foliar spray treatment with surfactant given no preplant N than the no N control treatment (Table 4.9). There were also minor differences due to preplant N rate in this trial with fewer live leaves per plant at the highest preplant N rate as compared with the treatment receiving 50% of the recommended N rate preplant (Table 4.9). On mineral soil in 2003 the carrots receiving the recommended N rate preplant and given foliar sprays with surfactant had a higher number of live leaves per plant than the other treatments (Table 4.9). In all other cases there were no effects of treatment on the number

Table 4.7. Effect of foliar nitrogen (N) application on Alternaria and Cercospora leaf blight area under the disease progress curve (AUDPC) for carrots grown on mineral and organic soil.

Treatment[z]	Alternaria AUDPC			Cercospora AUDPC		
	2002[y]	2003	2004	2002[y]	2003	2004
Organic						
0	347.4 b[x]	360.7 b	349.5 d	406.2 b	374.4 c	347.6 d
0 + Foliar	347.4 b	346.6 b	312.9 bc	404.8 b	365.6 a-c	300.8 b
0 + Foliar – S.	--	348.9 b	325.3 c	--	371.9 bc	325.1 c
50 + Foliar	332.9 ab	326.6 a	286.8 a	386.3 a	350.7 ab	268.5 a
100 + Foliar	311.0 a	324.2 a	294.3 ab	376.1 a	343.2 a	295.4 b
Mineral						
0	132.8 a	266.6 c	380.6 b	117.6 ab	209.7 b	367.3 bc
0 + Foliar	147.2 b	257.0 bc	391.9 b	128.9 b	182.7 a	387.9 d
0 + Foliar – S.	--	262.9 c	381.3 b	--	206.1 b	380.8 cd
50 + Foliar	134.1 ab	248.4 b	373.0 b	130.1 b	192.3 a	354.0 ab
100 + Foliar	128.1 a	230.2 a	346.3 a	110.7 a	181.0 a	348.1 a

[z] Numbers indicate percent of recommended N application rate. Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress. Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea once rows were 75% covered with Agral 90 surfactant (S) added in 2003 and 2004; (-S) = without surfactant.

[y] No surfactant applied in any treatment.

[x] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table 4.8. Effect of foliar nitrogen (N) application on Alternaria and Cercospora leaf blight lesions per leaf in mid-September for carrots grown on mineral and organic soil.

Treatment[z]	Alternaria Lesions per Leaf		Cercospora Lesions per Leaf	
	2003	2004	2003	2004
Organic				
0	4.05 b[y]	6.53 a	15.13 a	25.23 a
0 + Foliar	2.55 a	4.84 a	10.59 a	24.37 a
Mineral				
0	5.95 a	6.52 a	7.21 a	45.98 a
0 + Foliar	6.52 a	5.67 a	5.81 a	39.28 a

[z] Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea once rows were 75% covered with Agral 90 surfactant added in 2003 and 2004.

[y] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table 4.9. Effect of foliar nitrogen (N) application on the number of live leaves per plant at harvest for carrots grown on mineral and organic soil.

Treatment[z]	Live Leaves per Plant		
	2002[y]	2003	2004
Organic			
0	3.9 a[x]	4.8 a	3.5 a
0 + Foliar	3.5 a	5.1 a	4.6 bc
0 + Foliar – S.	--	5.2 a	3.8 ab
50 + Foliar	3.9 a	4.9 a	4.8 c
100 + Foliar	4.1 a	5.3 a	3.9 ab
Mineral			
0	4.2 a	2.7 a	2.5 a
0 + Foliar	4.5 a	2.8 a	2.5 a
0 + Foliar – S.	--	3.0 a	2.4 a
50 + Foliar	3.5 a	2.8 a	2.6 a
100 + Foliar	4.6 a	3.7 b	2.6 a

[z] Numbers indicate percent of recommended N application rate. Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress. Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea once rows were 75% covered with Agral 90 surfactant (S) added in 2003 and 2004; (-S) = without surfactant.

[y] No surfactant applied in any treatment.

[x] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

of live leaves per plant at harvest. ‘Idaho’ carrots had a higher number of live leaves per plant at harvest than ‘Fontana’ carrots on organic soil in all three years and on mineral soil in 2004, but there were no differences between the cultivars on mineral soil in 2002 and 2003 (Appendix 5).

Crop Observations: Within the same year, carrots in the foliar N application trials were observed to be much healthier looking than the carrots in the three-year N rate trials in the last two years of the study, even though they were separated by no more than 100 m. The only differences in canopy health among treatments within these trials occurred on mineral soil in 2003 (Figure 4.3). Fungicide drift from a neighbouring field reduced disease in portions of the trial late in the season on organic soil in 2004, which increased variability within this plot. No nutrient deficiencies other than N deficiency were visually noted in any of the foliar N application trials.

4.3.3 Cultivar vs. Leaf Blight Assessment

In the cultivar trial, ‘Bradford’ had a higher ALB damage rating than ‘Svr 712222’ and ‘Sunrise’ (Table 4.10). Among the coloured carrots, purple carrots had a higher ALB rating than the red, dark orange carrots and ‘Cellobunch’, and had higher CLB rating than the red and dark orange carrots (Table 4.10). Purple carrots also had higher sap NO_3-N concentrations than dark orange and ‘Cellobunch’ carrots. There were no relationships between disease severity and sap NO_3-N concentration in either of the trials or in the combination of the two (Table 4.10).

Figure 4.3. Difference in canopy health of carrots grown on mineral soil in 2003 caused by variable preplant nitrogen application rates and foliar nitrogen application. Plants in foreground were fertilized at the recommended N application rate.

Table 4.10. Late-season Cardy meter sap nitrate-N (NO_3-N) concentrations and Alternaria and Cercospora leaf blight ratings and linear correlation statistics for their comparison for cultivars grown on organic soil in two separate trials in 2004.

Trial/Cultivar	NO_3-N conc. $mg \cdot kg^{-1}$	Alt. Rating[z]	Cerc. Rating[z]	Linear Correlation Statistics			
				NO_3-N vs Alternaria		NO_3-N vs Cercospora	
				P	r	P	r
Cultivar Trial				0.8995	0.04	0.7924	0.09
Bradford	151 a[y]	5.7 b	3.7 a				
Fontana	266 a	4.0 ab	2.3 a				
Svr 712222	143 a	3.3 a	3.7 a				
Sunrise	130 a	2.3 a	1.7 a				
Coloured Carrot Trial				0.3165	0.33	0.2771	0.36
Red (W 104-3)[x]	222 ab	5.0 a	4.7 a				
Purple (W 106-3)	332 b	8.7 b	8.3 b				
Dark Orange (W 101-23)	210 a	6.0 a	4.7 a				
Cellobunch	115 a	6.7 a	6.3 ab				
Combined				0.0953	0.37	0.0624	0.39

[z] Rating scale: 0 = no symptoms, 2 = few lesions on leaves, 4 = numerous lesions on leaves, few on petioles, 6 = numerous lesions on leaves and petioles, 8 = half of leaves destroyed, 10 = all leaves destroyed.

[y] Numbers followed by the same letter within the same trial are not significantly different at P=0.05, Fisher's Protected LSD Test.

[x] Breeding line numbers (Phil Simon, University of Wisconsin, Madison).

4.3.4 Nitrogen Rate and ALB and CLB Severity in the Greenhouse

In greenhouse trials with controlled rates of N, there was no effect of N rate on sap NO_3-N concentrations prior to *A. dauci* inoculation or on ALB lesions per leaf (Table 4.11). Leaf senescence decreased with increased N rate (Table 4.11). There were no differences between the two cultivars in ALB lesions per leaf, sap NO_3-N concentration, or senescence rating (Appendix 5), and both cultivars showed similar responses to N rate. Consequently, combined data from the two cultivars are reported. In this trial a few inoculated leaves did not develop lesions, and a few more died before assessment, which increased variability. Correlation analysis on the data set without the dead leaf data revealed no correlation between the number of Alternaria lesions per leaf and sap NO_3-N concentration ($P=0.7727$, $r=0.07$), but there was a positive linear correlation between the number of Alternaria lesions per leaf and leaf senescence rating prior to inoculation ($P=0.0148$, $r=0.52$). When data from leaves that did not develop ALB lesions were removed (which could have occurred because of uneven spread of spores on the leaves) the linear correlation between Alternaria lesions per leaf and senescence rating was still positive with a higher value ($P=0.0010$, $r=0.74$). Alternaria lesions were evenly spread over the infected leaves and on the water agar test plates. However, there was some clustering of conidia observed, with approximately 33% of the conidia aggregated into large clusters and 33% of the conidia in clusters of 2 or 3 spores. There was a 95% spore germination rate in the water agar plates that were sprayed with conidial suspension on the date of carrot inoculation. No ALB symptoms developed on carrots sprayed with Tween 80 solution alone.

Table 4.11. Effect of nitrogen (N) application rate on Alternaria leaf blight lesions per leaf, nitrate-N (NO_3-N) concentration prior to inoculation, and senescence rating prior to inoculation of individual carrot leaves artificially inoculated with *Alternaria dauci* on plants grown in the greenhouse in silica sand.

N rate[z]	Alternaria Leaf Blight Lesions per Leaf	NO_3-N Concentration $mg \cdot kg^{-1}$	Senescence Rating[y]
50	3.17[x]	142.5[x]	3.3[w]
100	5.43	163.8	2.5
200	3.13	156.6	1.9

[z] % of the N required for a 50% Hoagland solution.
[y] Scale: 0 = leaf dark green, 2 = leaf light green, 4 = mild chlorosis, 6 = major chlorosis, 8 = partial necrosis, 10 = complete necrosis.
[x] Linear regression analysis not significant.
[w] Linear regression statistics: P=0.0196 R^2=0.44 Equation: rating=3.594 – 0.00866(N rate).

The number of Cercospora lesions per leaf was unaffected by N rate in the greenhouse on carrots grown on both sand and soilless mix, except for the first assessment on soilless mix, where the number of Cercospora lesions per leaf increased with increasing N rate (Table 4.12). Plant senescence rating prior to inoculation increased with increasing N rate for carrots grown on sand (Table 4.12). In all other cases there was no effect of N rate on plant senescence. Sap NO_3-N concentration prior to inoculation increased with increasing N rate on sand, but not soilless mix (Table 4.12). 'Idaho' carrots had more lesions per leaf at the 4-week assessment and a higher NO_3-N concentration at the final assessment than 'Fontana' carrots grown in sand (Appendix 5). 'Idaho' carrots had a lower senescence rating prior to *C. carotae* inoculation than 'Fontana' carrots in soilless mix (Appendix 5). In all other cases for both experiments there were no differences between the cultivars in lesions per leaf, senescence rating, or sap NO_3-N concentration (Appendix 5). Combined data from the two cultivars are reported since both cultivars responded in a similar manner to treatment. The number of Cercospora lesions per leaf decreased in relation to increasing sap NO_3-N concentrations and decreasing leaf senescence at the second assessment when data from both soil types were pooled (Table 4.13). No other linear correlations were found.

Potato dextrose agar plates sprayed with *C. carotae* conidial suspension showed little or no clustering of spores and a germination rate of 93%. Plates sprayed with the fine-mist hand sprayer had more even coverage with conidia and had more conidia per area assessed than plates sprayed with the artist airbrush. Although the sprayers appeared to evenly spread conidia over the leaves, lesions were highly variable among different leaves in each pot, with most lesions located on certain mid-aged leaves and very few on

Table 4.12. Effect of nitrogen (N) application rate on Cercospora leaf blight lesions per leaf, nitrate-N (NO_3-N) concentration prior to inoculation, and senescence rating prior to inoculation of carrots plants grown in silica sand and soil-less mix in the greenhouse and artificially inoculated with *Cercospora carotae*.

Treatment[z]	Lesions per Leaf		Senescence Rating[y]		NO_3-N conc. $mg \cdot kg^{-1}$	Final 2-leaf Analysis (6 weeks AI)[x]	
	4 weeks AI	6 weeks AI	Prior to Inoculation	6 weeks AI	Prior to Inoculation	NO_3-N conc. $mg \cdot kg^{-1}$	Lesions per Leaf
Sand							
50	0.21[w]	0.57[w]	2.7[v]	3.1[w]	456[u]	154[w]	10.38[w]
100	0.34	0.71	3.0	2.8	1230	233	2.13
200	0.55	1.19	3.4	3.1	2690	412	1.88
Soilless							
50	0.24[t]	1.37[w]	2.3[w]	2.5[w]	3288[w]	1349[w]	11.75[w]
100	0.09	0.81	2.1	3.0	3125	1306	9.00
200	0.84	2.23	1.9	2.4	3830	1796	27.50

[z] % of the N required for a 50% Hoagland solution.
[y] Scale (average of all leaves): 0 = dark green, 2 = light green, 4 = mild chlorosis, 6 = major chlorosis, 8 = partial necrosis, 10 = complete necrosis.
[x] 2 leaves collected at 6 weeks after inoculation (AI) and assessed for both nitrate-N content and Cercospora leaf blight lesions per leaf.
[w] Linear regression analysis not significant.
[v] Linear regression statistics: P=0.0161, R^2=0.49, Equation: rating=2.44 + 0.0451(N rate): one outlier removed for the analysis.
[u] Linear regression statistics: P=0.0204, R^2=0.43, Equation: [nitrate-N] = -273.50 + 14.849(N rate).
[t] Linear regression statistics: P=0.0336, R^2=0.41, Equation: lesions per leaf = -0.181 + 0.0042(N rate): one outlier removed for the analysis.

Table 4.13. Linear correlation statistics for the comparison of sap nitrate-N, senescence ratings, and Cercospora lesions per leaf for carrots grown at three different N rates in silica sand and soilless mix and artificially inoculated with *Cercospora carotae*.

Trial	Lesions per leaf vs. senescence rating				Lesions per leaf vs. sap nitrate-N					
	1st Assessment		2nd Assessment		1st Assessment		2nd Assessment[z]		Final 2-leaf Assessment	
	P	r	P	r	P	r	P	r	P	r
Sand	0.436	-0.17	0.177	-0.28	0.724	-0.08	0.021	0.47	0.279	-0.23
Soilless	0.293	-0.22	0.155	-0.30	0.130	-0.32	0.278	0.23	0.820	0.05
Combined	0.098	-0.24	0.022	-0.33	0.716	-0.05	0.015	0.35	0.102	0.24

[z] Cardy readings were from the final 2-leaf assessment, lesions per leaf was from the 2nd entire plant assessment.

similarly aged leaves within the same pot. On the leaves with numerous lesions, the lesions were evenly spread from the base of the petiole all the way to the tip of the leaf, suggesting that clustering of conidia did not occur. Carrots given the low N rate were stunted and had lighter green leaves than those in the medium N rate. Carrots given the high N rate had dark green leaves, exhibited some necrosis at the leaf tips, and were stunted compared to plants given the medium N rate. No Cercospora lesions developed on control plants sprayed with Tween 80 solution alone.

4.4 Discussion

4.4.1. Effects of N Application Rate on Disease Severity

Increasing rates of applied N reduced both ALB and CLB in field and greenhouse trials on both soil types and both cultivars, which shows that both diseases are involved in the relationship between N and leaf blight shown by Westerveld et al. (2003). There were no relationships between preplant available N and disease severity on mineral soil in 2004, but ALB and CLB severity decreased with increasing preplant available N in the top 30, 60 and 90 cm on organic soil in 2004. These results were consistent with the effects of preplant applied N, probably because preplant soil NO_3-N concentrations at each depth were relatively constant across all N application rates. For ALB, the results confirm the hypothesis that increasing N fertility decreases disease severity in the field. This is the first study to show a direct relationship specifically between N fertility in the field and ALB. It was not possible to rate leaf senescence due to N deficiency alone due to the presence of disease symptoms on all plants throughout the latter half of the growing season. However, the number of live leaves per plant at harvest increased as N rate increased, a result that is not likely due to leaf blight damage alone, based on visual

observations. In the greenhouse, there was a positive linear relationship between the number of Alternaria lesions per leaf and senescence rating. Therefore, the disease was more severe on leaves that were more senescent, which is similar to an earlier report showing that susceptibility of leaves increases as the leaf ages (Soteros, 1979). Since the senescence rating occurred prior to inoculation, the observed differences had to be due to N application rate and its effects on plant physiology. Thus, these data provide support for the hypothesis suggested by Vintal et al. (1999) that delayed leaf senescence in high fertility treatments causes a delay in ALB development, and less severe symptoms as a result. The data suggests that N was at least partially responsible for the effects observed by Vintal et al. (1999) and White et al. (1983) on the effects of N, P, and K together on ALB severity, but are contrary to reports by Langston and Hudgins (2002) that increasing N does not increase ALB severity. However, N application rate was only increased by 29% in the latter study (Langston and Hudgins, 2002). The results are similar to the responses to leaf senescence shown for other Alternaria diseases (Rotem, 1994). Ali and Roy (1981) showed that older leaves have a lower N concentration and higher disease susceptibility, but did not suggest that high N concentrations increase disease susceptibility.

Cercospora leaf blight was consistently decreased by increasing N rate in the field on both mineral and organic soil. This is the first study to show an effect of nutrition on CLB severity on carrots in the field. This result is in contrast to the early greenhouse studies conducted by Thomas (1943) that showed that increasing N rate increased the disease, and field studies conducted by Tremblay and Charbonneau (1993) on organic soils in Quebec that showed no correlation between leaf N concentration and CLB

severity. There was little relationship between CLB and senescence in the greenhouse studies. However, where a linear correlation was found it was negative, suggesting that there is more disease on leaves that are healthy than on those that are senescent. Since CLB is most severe on younger leaves (van Delden and Carisse, 1993; Kushalappa, 1994), this is not surprising. It also confirms observations in the field that CLB lesions are rarely seen on older and senescing leaves. Consequently, the mechanism for the relationship between N rate and CLB severity cannot be the same as suggested above for ALB.

The shape of the disease progress curve over the growing season was not affected by N application rate. The Linear and Gompertz models both provided a good fit with the data. The Gompertz model was shown to provide the best fit with data in a previous study on CLB disease progress (Kushalappa et al., 1989). There were no differences in the slope or fit of either model among cultivars, but data fitted the non-linear model better for mineral soil than for organic soil. The reason for the lack of differences in the shape of the disease progress curve among cultivars and treatments, despite differences in AUDPC, could be due to mid-season effects of N. Both ALB and CLB began for all treatments at the same time and final disease ratings were also similar. The main differences due to cultivar or N application rate occurred between the first and last disease ratings. Thus, there may be more influence of the first and last assessment dates in the fit of the models to the data, which would result in a reduction in the differences among cultivars and treatments. The better fit of both models on mineral soil could be explained by a shorter disease period, less levelling off of disease severity near harvest, and lower N availability compared to organic soil.

In the greenhouse, Cercospora lesions per leaf increased with increasing sap NO_3-N concentrations on carrots grown on sand, and with increasing N rate in the soilless mix. This was in contrast to the field studies, but matched the findings of the greenhouse study conducted by Thomas (1943). These observations could be explained by a possible effect of excessive N as the N rate increased. Although N rate did not have a significant effect on the number of Cercospora lesions per leaf, carrots grown at the highest N rate and lowest N rate often had more lesions per leaf numerically than those given the 25% Hoagland solution. This suggests that both N deficiency and excessive N cause increased disease. The effects of excessive N are a real concern for carrots in the field, as shown in Chapter 2. Soils with a low organic matter content have reduced ability to immobilize N and reduce the concentration of NO_3^- and NH_4^+ in soil solution. In the sand culture little or no immobilization would occur. Excessive N may cause leaf damage and could increase susceptibility to leaf blight. This same mechanism could explain the results of Thomas (1943). Thomas (1943) gave plants a 'complete nutrient solution as described by Hoagland and Arnon (1938)' applied through drip irrigation, and then half the plants were flushed with distilled water to cause deficiency. A 25% Hoagland solution was sufficient for optimum carrot growth throughout the current experiments, and seedling death and chlorosis and necrosis of the tops could be observed above this level. A 50% Hoagland solution alternating with tap water was also sufficient for carrot growth in a greenhouse experiment in Florida (Strandberg, 1988). If the plants were under excessive N levels in Thomas' experiment, then plants flushed with distilled water could have the toxic concentrations of N diminished resulting in reduced susceptibility to disease. Thomas assumed that the flushed plants had deficient N conditions and had lower

disease. However, it is possible that Thomas supplied a complete nutrient solution that was diluted, and did not include the dilution factor in the publication of his results.

The observation in the greenhouse that Cercospora lesions were predominately located on mid-aged leaves is consistent with previous research showing that young leaves are more susceptible to the disease (van Delden and Carisse, 1993), and by the time the lesions developed, the young leaves would have been mid-aged. The observation that one leaf within a pot had an even spread of numerous lesions and a similar leaf in the same pot had none is surprising. This observation was noted in numerous pots in both trials, both cultivars, and in all N rates. The even spread of lesions on those leaves that were highly infected suggests that conidia were applied evenly to the pots. High variability among leaves was also reported in the study conducted by van Delden and Carisse (1993). There are three possible explanations for this observation. First, leaves may only be highly susceptible to *C. carotae* infection during a narrow window during leaf development. If this hypothesis were true, only the leaves that were at that exact development stage would have been highly susceptible upon inoculation. However, previous research has shown a continuous and gradual decline in the susceptibility of carrot leaves to CLB as the leaf ages (van Delden and Carisse, 1993), which suggests that similarly aged leaves should have had a similar number of lesions per leaf. A second possible explanation is that leaf defences could only be penetrated if numerous conidia germinated and began penetration all at once. Defence structures and compounds require energy for their production and the spread of resources to many areas of the leaf could cause reduced effectiveness. It is possible that N availability could influence either mechanism by altering the length of the susceptible window, or by enhancing the

availability of defence related compounds and preventing successful infection. Finally, leaf wetness might have been variable within the plastic bags during the infection period. However, *C. carotae* can infect under conditions of high relative humidity without leaf wetness (Carisse et al., 1993), so variable leaf wetness should not have a pronounced effect on infection rate. These hypotheses, however, were not tested.

There is one mechanism that is at least partially responsible for the effect of N rate on both diseases, especially in the field. The effects of N on leaf growth are discussed in Chapter 3. However, in the high N treatments, a constant replacement of older diseased leaves throughout the season with newer leaves was observed in the field, whereas the plants in low N conditions appeared to produce fewer new leaves, especially late in the season. Disease ratings and the number of lesions per leaf would be lower in high N treatments even if there was the same total number of lesions per plant due to a dilution effect. This could be considered an increase in disease tolerance, since plants given high N rates could maintain top health by outgrowing the disease. This mechanism of disease response to applied N has been demonstrated for other diseases such as take-all of wheat and powdery mildew of barley (Last, 1963; Huber, 1980a). The production of new leaves could temporarily result in fewer photoassimilates available for root development, compared with carrots grown with low N. If it occurred immediately before harvest, it could partially explain why carrots with lower disease under high N conditions have the same yield, as shown in Chapter 2, as plants with higher disease under low N conditions.

Within a cultivar, both ALB and CLB decreased with increasing mean season-long sap NO_3-N concentrations. Plants with high sap NO_3-N concentrations had low

disease severity. However, 'Fontana', which had consistently higher disease severity than 'Idaho', also had consistently higher sap NO_3-N concentrations. Although there was no correlation between sap NO_3-N concentration and disease severity among cultivars in the cultivar and coloured carrot trials, the carrots with the highest disease severity also had the numerically highest sap NO_3-N concentrations. In the N rate studies where the cultivars remained constant, sap NO_3-N concentration probably provided an indication of overall N status of the plant, which was directly related to leaf senescence and disease development. When comparing different cultivars, NO_3-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 may reduce a different proportion of the NO_3^- taken up by the roots in the leaves. It is possible that cultivars that transport more N as NO_3^- to the leaves use more energy for N conversion in the leaves, leaving less energy for defence and defence related compounds, or they are restricted in their ability to convert NO_3-N to organic forms. However, production of zinniol, a phytotoxin produced by *A. dauci*, has been shown to be favoured by increasing concentration of organic N compounds such as asparagine (Barash et al., 1981), which could be higher in 'Idaho' than 'Fontana' if 'Fontana' carrots were restricted in their ability to convert NO_3^- to organic forms. Although 'Fontana' carrots always had higher sap NO_3-N concentrations, they also had much weaker tops and more senescent leaves than 'Idaho' carrots. Leaf production by 'Fontana' was improved through N application, especially on mineral soil in 2003 and 2004. This suggests that total N deficiency existed in these plants even though sap NO_3-N concentrations were very high. Overall, the hypothesis that cultivars exhibiting more susceptibility to ALB and CLB also transport less N to the leaves during

the time of pathogen infection and development can be rejected since more NO_3-N was transported in the highly susceptible cultivar 'Fontana' than the less susceptible cultivar 'Idaho'. It is also not likely that either disease is influenced by sap NO_3-N concentrations directly, since cultivars with high levels of NO_3-N have more disease, and treatments with high levels of NO_3-N have less disease.

4.4.2. Effects of Foliar N Application on Disease Severity

Foliar application of N provided minimal and variable effects on the severity of ALB and CLB. The differences among the foliar N treatments receiving three different rates of preplant N could be explained solely by the N rate effects noted in the N rate field experiments. There is no evidence to suggest that a combination of preplant and foliar N provided better resistance to leaf blight than either one alone. The 10 $kg \cdot ha^{-1}$ of N applied in the foliar sprays was very small compared to total N uptake of up to 380 $kg \cdot ha^{-1}$ by carrots over the season (Chapter 3). More frequent foliar N application might have had more effect, but the cost to the grower would also increase. An understanding of the efficiency of N application preplant or by foliar sprays for N nutrition of the leaves is required. Foliar sprays currently cannot be recommended as an effective management strategy for the control of leaf blight.

4.4.3. Implications for Agriculture

The results of the field and greenhouse experiments suggest that optimal N fertilization could be used to reduce the number of fungicide applications for the control of ALB and CLB. A study on the exact relationship between leaf blight severity and the ability to mechanically harvest the crop, and the integration of this data with the current

integrated crop management program is required before precise recommendations can be established. However, this study does show that growers who wish to reduce the amount of N applied to carrots could have an increase in disease severity if disease controls are not increased to compensate. It also shows that growers may be able to reduce the number of fungicide applications if N application is increased. The amount of reduction in fungicide sprays per unit N applied has yet to be determined. Overall, the use of fungicide and N application combined could result in improved disease control, reduced environmental contamination, and decreased resistance of *A. dauci* or *C. carotae* to fungicides. Combining control measures has proven to be more effective for ALB control than relying on one control measure (Ben-Noon et al., 2003).

4.5 Conclusions

Carrot susceptibility to ALB and CLB is influenced by the N nutrition of the plant, especially preplant. Nitrogen fertilization consistently reduced the severity of ALB and CLB in the field. This resulted in improved canopy health at harvest in high N conditions. There were no consistent differences in the response of ALB and CLB to N application rate among cultivars, soil types, or years. The decrease in ALB severity was partially due to delayed leaf senescence at high N application rates. Nitrogen was observed to increase disease tolerance to both diseases by increasing the production of new leaves. Disease severity increased with increasing leaf NO_3-N content, but the susceptibility of cultivars to leaf blight was not related to NO_3-N or total N concentration in the leaves. Foliar N application did not consistently decrease the severity of ALB or CLB. The results suggest that current season preplant N application or preplant soil N status have a large effect on ALB and CLB severity.

Chapter 5: General Discussion, Conclusions, and Future Research

5.1 General Discussion

5.1.1 Introduction

Management of vegetable crops requires integration of many distinct aspects of crop production including nutrition, pest management, and cultural practices. This study highlighted the importance of an integrated approach to N and disease management. Previous research focussed on the yield response to nitrogen (N) application and a few studies were conducted on the effects of plant nutrition on disease. This was the first study to integrate N and disease management of carrots, and to identify causal mechanisms for previous reports. In particular, this was the first study to identify an effect of crop nutrition in the field on the severity of Cercospora leaf blight (CLB), and the first study to show that N application alone affects the severity of Alternaria leaf blight (ALB) in the field. This was also the first study to identify broad mechanisms involved in the relationship between N and leaf blight. In the area of N nutrition of carrots, this study was first to determine the precise N requirements of carrots under Ontario growing conditions; and the first study to track DM and N uptake in the tops and roots over the growing season and to compare these among cultivars, soil types, and N application rates. Finally, this was the first study to develop an N budget of the carrot crop at different N application rates, and to assess the potential of carrots as an N catch crop.

The purpose of this chapter is to integrate the results of the previous chapters, to provide overall conclusions, and to highlight key areas that require further investigation.

5.1.2 Interrelationships Between Nitrogen and Alternaria and Cercospora Leaf Blight

Five mechanisms have been identified that explain N effects on disease incidence and severity (Colhoun, 1973; Huber, 1980b). This study focussed on two of these mechanisms: facilitating disease escape and increasing host tolerance to the disease. For both diseases, N was observed to increase host tolerance to the disease by increasing the ability of the plants to regenerate leaves that were destroyed by leaf blight. For ALB, N facilitated partial disease escape by delaying leaf senescence and delaying pathogen infection as a result. The other three main ways N affects disease: improving host structural and physiological defences, and decreasing pathogen virulence, involve N nutrition of the leaf and N concentration in the leaf. Nitrogen concentration of the leaf was examined to determine if these factors could be involved. Nitrogen concentration of the leaf increased with increasing N rate, suggesting that any of these three mechanisms could explain the effects of N on disease. The patterns of N uptake and distribution over the season provided no explanations for the effects of N application rate on leaf blight severity or the differences in leaf blight susceptibility between cultivars. Nitrogen uptake and distribution were not influenced by cultivar or by N application rate. Consequently, the differences between cultivars are probably related to differences in structural or chemical defences in the plants. In addition, it was observed that ‘Fontana’ had reduced ability to regenerate leaf material late in the season, which resulted in a greater number of diseased leaves per plant. However, there is the possibility that applied N could be

interacting with other nutrients or elements, resulting in an indirect relationship between N and leaf blight severity.

In a related study, linear correlation analysis was used to identify relationships among element concentrations in leaf and root tissues, and between element concentrations in the leaf and leaf blight severity (Appendix 6). Both leaf blight and total N concentrations were correlated with most of the elements tested in both leaf and root tissues in some cases. When the results of the two cultivars were combined, Na and Mg were better correlated with the AUDPC of ALB and CLB AUDPC than total N concentrations in 3 out of 4 cases (all 4 cases for Na and AUDPC of CLB). This suggests that the effects of N application rate on leaf blight severity might be the result of the interaction between N and concentrations of other elements in the leaf.

Nitrogen accumulation in tops was shown to occur primarily before 50 DAS in Chapter 3. This could provide some explanation for the minimal effect of sidedress N on ALB and CLB susceptibility of carrots. It is possible that the N required for defence against these pathogens accumulates prior to 50 DAS, and consequently, early season N uptake may be critical for plant defence. In Chapter 2 it was shown that new leaves accumulated twice as much ^{15}N during the three weeks after ^{15}N application than the old leaves, suggesting that old leaves were no longer important sinks for N. It may be that defence compounds are produced in the leaf during the time of leaf formation, and consequently, optimal N is required at this time. Beyond 50 DAS, the majority of the N taken up by the plant is partitioned to the storage root. At this time, the tops may be deficient in N, resulting in reduced effectiveness of later N application. Furthermore, NO_3^- reduction in the leaves has been shown to increase with increasing N supply

(Andrews, 1986), and is highest in young leaves and decreases as the plant ages (Darwinkel, 1975). This provides further support for the requirement of early season N in plant defence. This would explain why foliar N application had little effect on leaf blight susceptibility. Since N concentration of tops was not assessed following sidedress N application, the effectiveness of sidedress N for increasing leaf N content cannot be determined from this study. However, split applications of fertilizer did not decrease ALB severity compared to preplant applications in an earlier study (White et al., 1983).

5.1.3 Yield Effects of Leaf Blight

Major leaf infection and senescence of the carrot canopy occurred in all years of the study due to ALB and CLB. On mineral soil, it was not possible to distinguish the effects of leaf blight from those of N deficiency. However, on organic soil, no yield differences occurred among treatments despite differences in disease severity. Consequently, even though leaf blight resulted in a loss in leaf area during the period of peak DM production, there was no detectable effect on yield. Previous research showed a similar lack of effect of ALB on yield (White et al., 1983). The carrot plant must be able to compensate for the effects of leaf blight and avoid yield losses. Top re-growth was observed late in the season in severely infected plants, and this could result in improved DM production during this time. However, the production of new leaves would have to come at a cost of reduced DM accumulation in the roots. Peak levels of DM accumulation and N uptake occurred in August and September, which coincides with the period of greatest incidence and severity of leaf blight. This may not be coincidental. Rotem (1994), reviewing Alternaria diseases, suggested that yield is a stress factor because nutrients become less available to the leaf tissues upon the initiation of the

storage organ, which results in increased infection. Consequently, the period of rapid increase in DM partitioning to the roots at 50-60 DAS may correspond with a rapid increase in susceptibility to ALB, and perhaps CLB.

'Fontana' carrots had much higher disease severity over the season than 'Idaho' carrots, but the two cultivars had similar yields. This could be explained by differences in the proportion of DM partitioned to the roots. 'Fontana' was shown previously to be a high yielding cultivar (McDonald et al., 2003). Research has shown an increase in ALB susceptibility with an increase in the proportion of DM partitioned to the storage root in carrots (Rotem, 1994). Since 'Fontana' partitioned a higher proportion of DM to the roots than 'Idaho' in most cases, it is possible that this caused 'Fontana' to be more susceptible to leaf blight. The higher leaf blight damage could then reduce storage root yields and result in equal total yields between the cultivars. It is also possible that the loss of leaf area caused by ALB and CLB was not proportional to a loss in canopy photosynthesis (P_c). Previous work on carrot canopy lateral trimming, in which 40% of the canopy between rows was cut off in late August or early September to improve airflow, did not cause a loss in yield compared to untrimmed canopies (Kora et al., 2005). In addition, observations suggest that CLB often reduces photosynthetic area of younger leaves, but ALB more often results in complete senescence of older leaves. Consequently, the young leaves that would be more active in photosynthesis would remain less affected by ALB.

5.1.4 Leaf Blight and Nitrogen Sufficiency

An important result from this study is that N can be sufficient for optimal root growth while at the same time be deficient for plant defence in the canopy. Furthermore, visible symptoms of N deficiency in the tops did not correspond to a reduction in root

growth. This suggests that N deficiency first affects the leaves and then the storage roots. The results occurred despite N uptake values between 200 and 380 $kg \cdot ha^{-1}$. The visible symptoms of deficiency in the tops could have been induced by higher disease severity. It is also possible that the cause of the effect of N on disease is directly or indirectly related to the concentration of N in the leaves, which would be influenced by luxury N consumption regardless of the N sufficiency of the plant. Luxury N consumption could result in increased defence related compounds, or could influence the assimilation or concentration of other nutrients as discussed previously.

5.1.5 Timing of Nitrogen Application

Sidedress N application would have the advantage of reducing potential N losses due to leaching, and preventing seedling death through N toxicity. In Chapter 2 it was shown that preplant N had much more influence on yield than sidedress application. It was suggested that sidedress application must have been too late in the growing season and may not have been completely available to the crop. However, research presented in both Chapter 2 and Chapter 3 shows that the majority of N is taken up during August and September. Since sidedress N was applied in early July, the N should have been available at the time of maximum uptake. One explanation for the lack of effect could be that N uptake in the field occurs primarily deep in the soil profile. In the greenhouse experiments it was shown that N uptake is proportional to rooting density at each depth, and that a significant amount of roots occur below 30 cm depth. In the field, where frequent drying of the top 10 cm occurs, it is possible that a higher proportion of the rooting system was below 10-15 cm depth where water would be more available. Carrot roots have been shown to reach up to 38.5 cm depth by 24 DAS (White and Strandberg,

1978), and this suggests that deep N uptake could be substantial beyond 30 DAS. Since N leaching appeared to be relatively slow, given the effects of residual N from the previous season on yield in 2003 on mineral soil, it is possible that there was insufficient time following sidedress N application for the N to leach down into the active root zone. Although rainfall was adequate following sidedress N application in 2004, sidedress N was still not adequate to maintain yield. Heavy irrigation following sidedress N application could be a method to leach the N into the active root zone. However, the potential then exists for leaching to continue out of the active root zone and the N to be lost into the environment. Sidedress N was tested with timely irrigation in a previous study, but N deficiency did not occur in that study to compare the effects of preplant- and sidedress-applied N (Westerveld, 2002). Bienz (1965) showed that July sidedress application increases carrot root splitting, suggesting a root growth response to N applied at that time. Since carrots were irrigated in that study, it is possible that the July application was leached into the active root zone by the time of peak N uptake. Application of N in August resulted in no effect on splitting (Bienz, 1965), suggesting little effect on root growth at this time when the applied N would likely be in the upper layers of the soil profile and not accessible to the crop. Combined with the major effects of preplant-applied N on leaf blight severity, it is possible that shallow N at planting governs leaf blight susceptibility and deep N throughout the season governs yield potential. This is supported by the fact that N available in the top 60 cm was better related to yield than preplant N application rate or N available in the top 30 cm on mineral soil in 2004.

5.1.6 Timeline of Carrot Nitrogen Dynamics

Based on the results of this study and previous research, a timeline of N uptake, N partitioning, rooting depth, and interactions with yield and disease can now be proposed. Immediately following germination there is rapid development of the taproot, reaching a depth of 38.5 cm by 24 DAS (White and Strandberg, 1978). The tip of the taproot is probably out of the plow layer (top 15 cm) in mineral soil in about half that time. Nitrogen taken up during this time, which would have to occur in the upper layers of the soil profile, is mainly allocated to new leaf production, since N accumulation in the roots is minimal until 50-60 DAS based on this study and N accumulates in the leaves at a faster rate than DM prior to 50 DAS. Given the major effects of preplant N on leaf blight severity and the probability that all or most preplant-applied and mineralized N is in the upper 15 cm layer of soil profile at this time, it is possible that N taken up in the early growth period is critical for inducing leaf blight resistance for the entire life of the plant to both ALB and CLB. Defence of leaves to the leaf blight pathogens is probably conferred upon leaf formation and benefits from 'excess' N during this time. Since, leaf blight was affected by preplant N on organic soil, despite no effects of applied N on yield, it is likely that the N requirement for optimum formation of plant defences is much higher than that of carrot root or leaf production.

At 20-30 DAS the storage tissue in the root is initiated (Esau, 1940), and possibly coincides with penetration of the taproot into the subsoil. However, accumulation of the majority of N and DM at a rapid rate does not begin until 50-60 DAS based on this study and earlier reports (Platenius, 1934; Hole et al., 1983; Rubatzky et al., 1999; Reid and English, 2000; Strandberg, 2001). Beyond 24 DAS, the root must penetrate down the soil profile at an average rate of >1 $cm \cdot d^{-1}$, since roots reach a depth of 100 cm before 70

DAS in sandy soils (Thorup-Kristensen and van den Boogaard, 1999). Since sidedress N was applied between 30 and 60 DAS and had much less effect on yield than preplant-applied N, less N must be taken up in the upper layers of the soil profile beyond 40-60 DAS than earlier in the season. However, there must be some effect of sidedress N on the storage root, since high sidedress N applications induce splitting (Bienz, 1965). The rooting depth studies and ^{15}N work showed that N uptake was proportional to the number of roots present at each depth, and since >50% of the roots occurred below 30 cm depth in sand, it suggests that subsoil N may be critical for yield after this point. It is probable that N taken up beyond 40 DAS is transported primarily towards the leaves, metabolized and then reallocated back to the roots, as demonstrated in the ^{15}N studies and in observations of dye movement in carrot roots, which showed that new leaves recovered more N than the storage root by three weeks after application and dye taken up below the storage root is transported directly to the leaves. Thus, it is likely that deep N, i.e. subsoil N below 30 cm, and ability of roots to penetrate and forage in the subsoil zone governs much of the N related yield potential of carrots beyond this point.

Between 30 and 50 DAS, leaf production and N accumulation in the leaves begin to increase at a rapid rate. By 50-60 DAS, storage root DM and N accumulation accelerate rapidly. Growth of both the root and leaves occurs proportional to days between 50 and 100 DAS. At this time the majority of N that accumulates by harvest is taken up, and most is likely from below 30 cm depth. The N uptake during this period must be primarily from residual N from the previous seasons and preplant-applied or mineralized N that has leached down the soil profile, depending on the frequency of leaching rain or irrigation events. Beyond 100 DAS, there is net re-distribution of DM

and N from the leaves to the roots (Platenius, 1934), resulting in minimal further leaf growth, unless the canopy is decimated by leaf blight. At this time, plants supplied with insufficient N re-distribute DM and N from the older leaves to the root first, resulting in accelerated leaf senescence and increased ALB severity. Although weather conditions become less favourable for carrot growth during this period, the re-distribution from the leaves and continued photosynthesis in the leaves results in continued linear growth of the storage root until harvest.

5.1.7 Nitrogen Use Efficiency and Fertilizer Nitrogen Recovery

This is the first study to demonstrate that the apparent NUE of carrots is not due to an ability to produce DM with minimal available N, but due to uptake of N from mineralized and residual soil N that is not accounted for in the calculation of NUE. Fertilizer N recovery was low when N was applied, and N application was necessary to minimize foliar disease. Thus, carrot is a good scavenger of soil N, but not a good user of applied N. However, the minimal requirement of carrots for N application can be used to create a crop rotation with high NUE, since N applied to a crop with low NUE can be followed by a carrot crop that would capture the N remaining in the soil profile. This is confirmed by previous research showing that rotating deep- and shallow-rooted crops improves NUE of the rotation (Thorup-Kristensen, 2002).

5.1.8 Implications for Ontario Agriculture

Nitrogen Recommendations

There is no single recommendation for N application to carrots that will work in all years. On organic soil, there was no effect of N rate on yield in any of the three years,

despite repeated mining of soil residual N by successive crops. Consequently, on established organic soils, carrots do not require supplemental N fertilization to produce maximum yields. It is unknown if this lack of N effect on yield would continue to occur if carrots were grown for longer than three years on the same site. However, leaf blight severity decreased with increasing N application rate. Since leaf blight and related leaf senescence can directly reduce the amount of harvested crop, reducing the amount of N applied to the crop could result in major economic losses. Currently leaf blight can be adequately controlled using an extensive fungicide spray program. Consequently, the results from this study suggest that the N recommendation for organic soil should be as follows:

If leaf blight is adequately controlled by fungicide applications, no N should be applied to carrots on established organic soils. Application of N up to 90 kg·ha^{-1} has no negative effects on carrots on organic soil but should only be applied as a means to reduce the number of fungicide sprays applied to control ALB and CLB. Application of >90 kg·ha^{-1} can increase ALB severity.

Many growers in the Holland Marsh have not applied N to carrots when grown following onions for the past few decades. Specific numbers for the magnitude of the reduction in the number of fungicide sprays cannot be established based on the results of this study. The N budget study suggests that the risk of N leaching on organic soil is minimal compared to other crops even with 90 kg·ha^{-1} applied, since up to 250 kg·ha^{-1} N is removed from the field.

On mineral soil, yield, leaf blight, and stand effects complicate N recommendations. Under-application of fertilizer results in N deficiency and increased

leaf blight severity, while over-application of fertilizer results in reduced stand and yield. Yearly differences in optimum N requirements make it difficult to establish a single N recommendation. In 2002, there was no effect of N application on yield, a result likely due to residual N from deep in the soil profile. In 2003, yield increased with N application up to 200% of the recommended rate or 220 $kg \cdot ha^{-1}$. In 2004, the maximum yield occurred near 100 $kg \cdot ha^{-1}$ and yield declined above that rate because of the effects of N on stand. These N rates were split 66% preplant and 33% sidedressed one month later. Using the assumption that yield followed a quadratic relationship with N in all years on mineral soil, despite no significant differences among treatments in 2002, consistent critical soil nitrate-N (NO_3-N) concentrations were observed for the early sampling date in mid-July. However, sidedress N after this point may not be effective in reducing any N deficiencies observed in mid-July. Overall, a single N recommendation is not possible for mineral soil. The results suggest that the following recommendations are most appropriate for carrots grown on mineral soil using the current knowledge of yield, stand, and leaf blight effects:

Carrots require an N supply at seeding of around 165 $kg \cdot ha^{-1}$ N in the top 60 cm of the soil profile under Ontario growing conditions, rain-fed, and in sandy soils with 2-3% OM content. Beyond this rate there is potential for increased yields but a risk of causing seedling death and decreased stand, possibly from stimulation of damp-off organisms. The ability of roots to penetrate into the subsoil is important for optimum N uptake. A model for estimating N application rates under these conditions can be based on soil NO_3-N concentration and the following equation: preplant N application rate ($kg \cdot ha^{-1}$) = 165 – [(NO_3-N concentration in the top 30 cm in $mg \cdot kg^{-1}$ + NO_3-N

concentration in the 30-60 cm zone in mg·kg^{-1}) x 4]. If applied preplant N is less than 100 kg·ha^{-1} based on this equation there is a risk for increased leaf blight, and additional fungicide sprays may be required later in the season. Although preplant N provides more benefit to the crop, sidedress N application of less than 100 kg·ha^{-1} could potentially improve yield if preplant N is insufficient and if applied prior to 60 DAS, but only if sufficient water is applied to leach N into the active root zone. Nitrogen sufficiency of the crop at 50 DAS can best be evaluated by testing soil NO_3-N concentrations using a Cardy nitrate meter, which should not be below 35 mg·kg^{-1}. There is increased risk of carrot splitting if N is applied around 50 DAS when the storage root is actively growing.

Further testing of the 165 kg·ha^{-1} N soil N supply factor is required, since it was based on one year of data, in carrot monocrop, and rain-fed conditions. It is likely that the N requirement for optimum yield would be higher in an irrigated crop. Testing should be conducted on several mineral soil types, with and without irrigation, and using different NO_3-N testing procedures to identify applicability, required adjustments, and more specific recommendations. However, specific recommendations for carrot N nutrition are no longer made in Prince Edward Island, where a lack of carrot response to N application was found in field trials (PEI Dept. of Agriculture, Fisheries, and Aquaculture, 2005). Foliar N application has potential to increase yields, but timing and rates of application require investigation before it can be used to reduce leaf blight severity.

5.2 Overall Conclusions

The results of this study have lead to the following conclusions:

1. Nitrogen application rate has no effect on total yield of carrots grown on organic soil, but causes variable effects on yield on mineral soil depending on residual soil N and weather conditions.
2. Nitrogen application rate has no effect on carrot storage root quality or storability.
3. Nitrogen application rates above current recommendations can lead to seedling death and a reduced stand on mineral soil, an effect that is increased in carrot monocropping.
4. Preplant N has more influence on yield potential than sidedress or foliar N application.
5. Increases in N application rate cause a reduction in ALB and CLB severity over the growing season and improved canopy health at harvest.
6. A decrease in ALB with increasing N application rate is at least partially caused by delayed leaf senescence.
7. The effects of N application rate on ALB and CLB cannot be explained by differences in DM or N partitioning over the growing season.
8. The differences in ALB and CLB susceptibility between cultivars cannot be explained by total N or NO_3-N concentrations in leaf tissues, rooting depth or distribution in the soil profile, or by DM or N partitioning over the growing season.
9. Carrots can be effectively used as an N catch crop on organic or mineral soil.
10. Total N uptake and removal values for carrots on organic soil are comparable to previously reported values for cole crops.

11. Total N and DM partitioning in carrot roots is negligible prior to 50-60 DAS and increases linearly beyond 50-60 DAS until harvest.
12. Carrots are capable of deep rooting up to 150 cm depth or more, and N uptake is proportional to the amount of roots present at each depth.
13. Carrots exhibit high NUE based on N applied, but this is primarily due to uptake of mineralized and residual N that is not accounted for in the calculation of NUE, and they exhibit low FNR.

5.3 Future Research

Future research should continue to identify causal mechanisms for the relationship between N and disease. For ALB, further data is required on the relationship between leaf senescence, N, and disease. Field trials should be conducted in which various N application rates are applied and the level of leaf senescence determined in the absence of disease; and within a single N application rate, disease severity should be rated on leaves at differing stages of leaf senescence. For CLB, research should focus on structural or chemical defences in the leaf tissues. Specifically, the levels of cercosporin production by the pathogen and 6-methoxymellein production by the host should be determined at different levels of N sufficiency in the leaves, since these compounds are reported as being important for *C. carotae* pathogenicity and carrot resistance. Furthermore, the relationships between disease severity and the concentration of other elements in the leaf should be investigated further for both diseases. The relationships between Na and Mg concentration in the leaf and disease severity should be examined for any direct or

indirect effects on the pathogens, since these elements are highly correlated with disease severity.

Another priority should be research on N uptake and partitioning between seed germination and 50 DAS. This could help to improve the timing of N application, and to determine the critical stages for N application and the critical concentrations of N in the soil and tissue at these stages. Furthermore, studies should attempt to relate early-season leaf N concentration to the susceptibility of carrots to ALB and CLB and in relation to defence compounds and structures in the leaf. A quantification of N uptake from different depths of the soil profile in the field is also required, including the timing of N uptake from different depths in the soil profile over the season. Injection of ^{15}N-enriched fertilizer at various depths in the soil profile throughout the season could be used to quantify N uptake. Methods to improve the efficiency of N application and the efficacy of mid-season N applications could then be established.

The causal mechanisms for the effects of N on seedling emergence require further investigation. Research should focus on damping-off pathogens or direct N toxicity as possible causes. Since the effects of N on stand were inconsistent from year to year, possible interactions with weather conditions should be investigated. The period of greatest N effect on the seedlings appears to be from seed germination to the time of first true leaf emergence.

5.3.1 Applied Research

An economic analysis of the effects of N and fungicides for ALB and CLB control is required. Specifically, research should focus on the number of fungicide sprays that can be eliminated with each incremental increase in N application. In addition, since

fungicide trials typically are conducted at the recommended N application rate, future research should determine if an increase in fungicide applications is required if N application rates are reduced.

Since the use of a single recommended N application rate could not be established on mineral soil, more research is required on the use of preplant or pre-sidedress soil NO_3-N tests. A method to account for soil residual N at seeding in all levels of the soil profile is required to adjust preplant N application rates on mineral soil. Methods to account for organic matter content of the soil are also required.

Foliar N application had inconsistent effects on yield and leaf blight severity in this study. Further research is required to test foliar N application at different times of day, different frequencies over the growing season, and with different rates of urea.

Sidedress N was shown to have less effect on yield than preplant-applied N on mineral soil despite the fact that the majority of N over the season is taken up in August and September. Furthermore, sidedress N increased root splitting. Research is required on different methods of sidedress N application such as fertigation to determine if they can be used to leach N into the active root zone to improve the effectiveness of mid-season N applications and reduce the dependence on large preplant N applications that could reduce seedling survival. In addition, methods to reduce the effects of sidedress N on carrot splitting require investigation in order for late sidedress N application to be practical and effective.

References

Abraham, V., A.C. Kushalappa, O. Carisse, G. Bourgeois, and P. Auclair. 1995. Comparison of decision methods to initiate fungicide applications against Cercospora blight of carrot. Phytoprotection 76: 91-99.

Agrios, G.N. 1997. Plant Pathology.Fourth Edition. Academic Press, New York.

Ali, M.S. and A.K. Roy. 1981. Sugar, tannin and nitrogen content of carrot leaves in relation to their susceptibility to *Alternaria* leaf blight. Science and Culture 47: 362-363.

Améziane, R., M.A. Limami, G. Noctor, and J.-F. Morot-Gaudry. 1995. Effect of nitrate concentration during growth on carbon partitioning and sink strength in chicory. Journal of Experimental Botany 46: 1423-1428.

Améziane, R., C. Richard-Molard, E. Deléens, J.-F. Morot-Gaudry, and M.A. Limami. 1997. Nitrate ($^{15}NO_3$) limitation affects nitrogen partitioning between metabolic and storage sinks and nitrogen reserve accumulation in chicory (*Cichorium intybus* L.). Planta 202: 303-312.

Andrews, M. 1986. The partitioning of nitrate assimilation between root and shoot of higher plants. Plant, Cell and Environment 9: 511-519.

Anonamous. 1997. Soil and plant analytical methods. Western States Laboratory Proficiency Testing Program.

Armstrong, M.J., G.F.J. Milford, T.O. Pocock, P.J. Last, and W. Day. 1986. The dynamics of nitrogen uptake and its remobilization during the growth of sugar beet. Journal of Agricultural Science 107: 145-154.

Arora, P.N. and R.B.L. Mathur. 1972. Note on effect of nitrogen and potash on the yield of carrots. Indian Journal of Agronomy 17: 116-117.

Assante, G., R. Locci, L. Camarda, L. Merlini, and G. Nasini. 1977. Screening of the genus *Cercospora* for secondary metabolites. Phytochemistry 16: 243-247.

Bakker, C.J. 2005. Nitrogen management of broccoli (*Brassica oleracea* var. *Italica*). M.Sc. Thesis, University of Guelph, Guelph, Ontario, Canada.

Barash, I., H. Mor, D. Netzer, and Y. Kashman. 1981. Production of zinniol by *Alternaria dauci* and its phytotoxic effect on carrot. Physiological Plant Pathology 19: 7-16.

Barclay, G.M., H.J. Murphy, F.E. Manzer, and F.E. Hutchinson. 1973. Effects of differential rates of nitrogen and phosphorus on early blight of potatoes. American Potato Journal 50: 42-48.

Barna, B. and B. Györgyi. 1992. Resistance of young versus old tobacco leaves to necrotrophs, fusaric acid, cell wall-degrading enzymes and autolysis of membrane lipids. Physiological and Molecular Plant Pathology 40: 247-257.

Bavaresco, L. and R. Eibach. 1987. Investigations on the influence of N fertilizer on resistance to powdery mildew (*Oidium tuckeri*) downy mildew (*Plasmopara viticola*) and on phytoalexine synthesis in different grapevine varieties. Vitis 26: 192-200.

Bazier, R., A. Guerillot-Vinet, and J. Guerillot. 1966. Effect of some fertilizers on amino-acids in wheat grain and carrot roots. Annals of Agronomy 17: 673-686.

Ben-Noon, E., D. Shtienberg, E. Shlevin, and A. Dinoor. 2003. Joint action of disease control measures: A case study of Alternaria leaf blight of carrot. Phytopathology 93: 1320-1328.

Bentz, J.A. and A.M. Townsend. 2003. Nitrogen fertilization and use of container-grown maple selections as hosts by the potato leafhopper. Journal of the American Society for Horticultural Science 128: 821-826.

Berendse, F. and R. Aerts. 1987. Nitrogen-use-efficiency: a biologically meaningful definition? Functional Ecology 1: 293-296.

Bienz, D.R. 1965. Carrot splitting and second growth in central Washington as influenced by spacing, time of sidedressing and other cultural practices. Journal of the American Society for Horticultural Science 86: 406-410.

Bishop, R.F., E.W. Chipman, and C.R. MacEachern. 1973. Effect of nitrogen, phosphorus and potassium on yields and nutrient levels in carrots grown on sphagnum peat and mineral soils. Communications in Soil Science and Plant Analysis 4: 455-474.

Blanc, D., S. Mars, and C. Otto. 1979. The effects of some exogenous and endogenous factors on the accumulation of nitrate ions by carrot root. Acta Horticulturae 93: 173-185.

Burdine, H.W. and C.B. Hall. 1976. Carrot responses to fertilizer levels on Everglades organic soils. Proceedings of the Florida State Horticultural Society 89: 120-125.

Burns, I.G. 1994. Studies of the relationship between the growth rate of young plants and their total-N concentration using nutrient interruption techniques: theory and experiments. Annals of Botany 74: 143-157.

Caldwell, P.M., J.M.J. Ward, N. Miles, and M.D. Laing. 2002. Assessment of the effects of fertilizer applications on gray leaf spot and yield in maize. Plant Disease 86: 859-866.

Carisse, O. and A.C. Kushalappa. 1990. Development of an infection model for *Cercospora carotae* on carrot based on temperature and leaf wetness duration. Phytopathology 80: 1233-1238.

Carisse, O., A.C. Kushalappa, and D.C. Cloutier. 1993. Influence of temperature, leaf wetness, and high relative humidity duration on sporulation of *Cercospora carotae* on carrot leaves. Phytopathology 83: 338-343.

Chen, Q., X. Li, D. Horlacher, and H.-P. Liebig. 2004. Effects of different nitrogen rates on open-field vegetable growth and nitrogen utilization in the North China Plain. Communications in Soil Science and Plant Analysis 35: 1725-1740.

Clark, C.A. and J.W. Lorbeer. 1976. The development of *Botrytis squamosa* and *B. cinerea* on onion leaves as affected by exogenous nutrients and epiphytic bacteria, p. 607-625. In: Dickinson, C.H., Preece, T.H. (eds.). Microbiology of aerial plant surfaces. Academic Press, New York.

Colhoun, J. 1973. Effects of environmental factors on plant disease. Annual Review of Phytopathology 11: 343-364.

Couper, G. 2001. The biology, epidemiology and control of *Sclerotinia sclerotiorum* on carrots in North East Scotland. PhD, University of Aberdeen, Aberdeen, Scotland, UK.

Darwinkel, A. 1975. Aspects of assimilation and accumulation of nitrate in some cultivated plants. Agricultural Research Reports, Wageningen 843: 64.

Esau, K. 1940. Developmental anatomy of the fleshy storage organ of *Daucus carota*. Hilgardia 13: 175-209.

Evers, A. 1988. Effects of different fertilization practices on the growth, yield and dry matter content of carrot. Journal of Agricultural Science in Finland 60: 135-152.

Fancelli, M.I. and H. Kimati. 1991. Occurrence of iprodione resistant strains of *Alternaria dauci*. Summa Phytopathologica 17: 135-146.

Fink, M. and H.C. Scharpf. 2000. Apparent nitrogen mineralization and recovery of nitrogen supply in field trials with vegetable crops. Journal of Horticultural Science and Biotechnology 75: 723-726.

Food and Agriculture Organization of the United Nations. 2004. Agricultural Statistics. http://apps.fao.org/faostat/.

Fream, W. 1905. Elements of Agriculture.7th ed. The Royal Agricultural Society of England, London.

Gallegly, J., M.E. and J.C. Walker. 1949. Plant nutrition in relation to disease development. V. bacterial wilt of tomato. American Journal of Botany 36: 613-623.

Ghini, R., W. Bettiol, J.F. Dynia, and A.H.N. Maia. 2001. Effect of nitrogen fertilizers on the soil suppressiveness to plant pathogens. Ecossistema 26: 147-151.

Goh, K.M. and N.S. Ali. 1983. Effects of nitrogen fertilisers, calcium and water regime on the incidence of cavity spot in carrot. Fertilizer Research 4: 223-230.

Gowda, R.V., C.S. Pathak, and G. Ganeshan. 2000. Resistance source for powdery mildew and alternaria leaf blight diseases in carrot. Journal of Tropical Agriculture 38: 84-86.

Gracie, A.J. and P.H. Brown. 2004. Effects of climatic factors, fluctuating water availability and partial defoliation on the diurnal radial growth pattern of carrot (*Daucus carota*) taproots. Australian Journal of Experimental Agriculture 44: 1231-1240.

Graham, R.D. 1983. Effect of nutrient stress on susceptibility of plants to disease with particular reference to the trace elements. Advances in Botanical Research 10: 221-276.

Gutezeit, B. 1999. Yield and nitrate content of carrots (*Daucus carota* L.) as affected by nitrogen supply. Acta Horticulturae 506: 87-91.

Hamilton, H.A. and R. Bernier. 1975. N-P-K fertilizer effects on yield, composition and residues of lettuce, celery, carrot and onion grown on an organic soil in Quebec. Canadian Journal of Plant Science 55: 453-461.

Hare, R.C. 1966. Physiology of resistance to fungal diseases in plants. Botanical Review 32: 95-137.

Hartz, T.K., P.R. Johnstone, and J.J. Nunez. 2005. Production environment and nitrogen fertility affect carrot cracking. HortScience 40: 611-615.

Hartz, T.K., R.F. Smith, M. LeStrange, and K.F. Schulbach. 1993. On-farm monitoring of soil and crop nitrogen status by nitrate-selective electrodes. Communications in Soil Science and Plant Analysis 24: 2607-2615.

Havis, L. 1939. Anatomy of the hypocotyl and roots of *Daucus carota*. Journal of Agricultural Research 58: 557-564.

Heilmeier, H., M. Freund, T. Steinlein, E.-D. Schulze, and R.K. Monson. 1994. The influence of nitrogen availability on carbon and nitrogen storage in the biennial

Cirsium vulgare (Savi) Ten. I. storage capacity in relation to resource acquisition, allocation and recycling. Plant, Cell and Environment 17: 1125-1131.

Hemphill, D.D., Jr. and T.L. Jackson. 1982. Effect of soil acidity and nitrogen on yield and elemental concentration of bush bean, carrot, and lettuce. Journal of the American Society for Horticultural Science 107: 740-744.

Hipp, B.W. 1978. Response by carrots to nitrogen and assessment of nitrogen status by plant analysis. HortScience 13: 43-44.

Hoagland, D.R. and D.I. Arnon. 1938. The water-culture method for growing plants without soil. University of California, College of Agriculture, Agricultural Experiment Station. Berkeley, California. Circular 347:1-39.

Hochmuth, G.J., J.K. Brecht, and M.J. Bassett. 1999. Nitrogen fertilization to maximize carrot yield and quality on a sandy soil. HortScience 34: 641-645.

Hole, C.C., A. Barnes, T.H. Thomas, P.A. Scott, and W.E.F. Rankin. 1983. Dry matter distribution between the shoot and storage root of carrot (*Daucus carota* L.). Annals of Botany 51: 175-187.

Hole, C.C. and J. Dearman. 1991. Carbon economy of carrots during initiation of the storage root in cultivars contrasting in shoot:root ratio at maturity. Annals of Botany 68: 427-434.

Hole, C.C., G.E.L. Morris, and A.S. Cowper. 1987a. Distribution of dry matter between shoot and storage root of field-grown carrots. II. relationship between initiation of leaves and storage roots in different cultivars. Journal of Horticultural Science 62: 343-349.

Hole, C.C., G.E.L. Morris, and A.S. Cowper. 1987b. Distribution of dry matter between shoot and storage root of field-grown carrots. III. development of phloem and xylem parenchyma and cell numbers in the storage root. Journal of Horticultural Science 62: 351-358.

Hooker, W.J. 1944. Comparative studies of two carrot leaf diseases. Phytopathology 34: 606-612.

Huber, D.M. 1980a. The role of mineral nutrients and agricultural chemicals in the incidence and severity of take-all. In: Shipton, P.J., Asher, M. (eds.). The biology and control of take-all. Academic Press, New York.

Huber, D.M. 1980b. The role of mineral nutrition in defense, p. 381-406. In: Horsfall, J.G., Cowling, E.B. (eds.). Plant disease: an advanced treatise. Academic Press, Toronto.

Huber, D.M. and R.D. Graham. 1999. The role of nutrition in crop resistance and tolerance to diseases, p. 169-204. In: Rengel, Z. (ed.). Mineral nutrition of crops; fundamentals, mechanisms, and implications. Food Products Press, New York.

Huber, D.M. and R.D. Watson. 1974. Nitrogen form and plant disease. Annual Review of Phytopathology 12: 139-165.

Jackson, M.A. and R.J. Bothast. 1990. Carbon concentration and carbon-to-nitrogen ratio influence submerged-culture conidiation by the potential bioherbicide *Colletotrichum truncatum* NRRL 13737. Applied and Environmental Microbiology 56: 3435-3438.

Johnson, R.D., L. Johnson, Y. Itoh, M. Kodama, H. Otani, and K. Kohmoto. 2000. Cloning and characterization of a cyclic peptide synthetase gene from *Alternaria alternata* apple pathotype whose product is involved in AM-toxin synthesis and pathogenicity. Molecular Plant-Microbe Interactions 13: 742-753.

Jones, J.B.J. 1999. Soil analysis handbook of reference methods. Soil and Plant Analysis Council.

Kaack, K., M. Nielsen, L.P. Christenson, and K. Thorup-Kristensen. 2001. Nutritionally important chemical constituents and yield of carrot (*Daucus carota* L.) roots grown organically using ten levels of green manure. Acta Agriculturae Scandinavica 51: 125-136.

Kachanoski, R.G. and G.L. Fairchild. 1996. Field scale fertilizer recommendations: the spatial scaling problem. Canadian Journal of Soil Science 76: 1-6.

Kay, B.D., R. Pararajasingham, R.S. Dharmakeerthi, A.A. Mahboubi, and E.G. Beauchamp. 2004. Spatial versus temporal variation in N mineralization in a landscape: relation to organic carbon contents and weather. Ontario Nitrogen Forum, Niagara Falls, Ontario. p. 1-10.

Király, Z. 1964. Effect of nitrogen fertilization on phenol metabolism and stem rust susceptibility of wheat. Journal of Phytopathology 51: 252-261.

Király, Z. 1976. Plant disease resistance as influenced by biochemical effects of nutrients in fertilizers. 12th Colloquium of the International Potash Institute, Izmir, Turkey. p. 33-46.

Kora, C., M.R. McDonald, and G. Boland. 2005. Lateral clipping of canopy influences the microclimate and development of apothecia of *Sclerotinia sclerotiorum* in carrots. Plant Disease 89: 549-557.

Kristensen, H.L. and K. Thorup-Kristensen. 2004. Uptake of ^{15}N labeled nitrate by root systems of sweet corn, carrot, and white cabbage from 0.2-2.5 meters depth. Plant and Soil 265: 93-100.

Kumazawa, K. 2002. Nitrogen fertilization and nitrate pollution in groundwater in Japan: Present status and measures for sustainable agriculture. Nutrient Cycling in Agroecosystems 63: 129-137.

Kusaba, M. and T. Tsuge. 1995. Phylogeny of *Alternaria* fungi known to produce host-specific toxins on the basis of variation in internal transcribed spacers of ribosomal DNA. Current Genetics 28: 491-498.

Kushalappa, A.C. 1994. Cercospora leaf blight, p. 67-68. In: Howard, R.J., Garland, J.A., Seaman, W.L. (eds.). Diseases and pests of vegetable crops in Canada: an illustrated compendium. The Canadian Phytopathological Society and Entomological Society of Canada, Ottawa.

Kushalappa, A.C., G. Boivin, and L. Brodeur. 1989. Forecasting incidence thresholds of Cercospora blight of carrots to initiate fungicide application. Plant Disease 73: 979-983.

Lampkin, N. 1990. Organic Farming. Farming Press, Miller Freeman plc, Ipswich, UK.

Langenberg, W.J. 1975. Carrot leaf blight (*Alternaria dauci*) development in relation to environmental factors and fungicide applications, University of Guelph, Guelph.

Langston, D.B.J. and J.E. Hudgins. 2002. Evaluation of fungicides and protection intervals for control of Alternaria leaf spot of carrot using two nitrogen fertility regimes. Fungicide and Nematicide Tests 57: V019.

Last, F.T. 1962. Effects of nutrition on the incidence of barley powdery mildew. Plant Pathology 11: 133-135.

Lebeda, A., J. Coufal, and P. Kvasnicka. 1988. Evaluation of field resistance of *Daucus carota* cultivars to *Cercospora carotae* (carrot leaf spot). Euphytica 39: 285-288.

Lewis, J.A., R.D. Lumsden, P.D. Millner, and A.P. Keinath. 1992. Suppression of damping-off of peas and cotton in the field with composted sewage sludge. Crop Protection 11: 260-266.

Lund, R.E. 1975. Tables for an approximate test for outliers in linear models. Technometrics 17: 473-476.

Lynch, J. 1998. The role of nutrient-efficient crops in modern agriculture, p. 241-264. In: Rengel, Z. (ed.). Nutrient use in crop production. The Haworth Press, Inc., New York.

MacDonald, A.J., D.S. Powlson, P.R. Poulton, and D.S. Jenkinson. 1989. Unused fertilizer nitrogen in arable soils - its contribution to nitrate leaching. Journal of the Science of Food and Agriculture 46: 407-419.

MacKenzie, D.R. 1981. Association of potato early blight, nitrogen fertilizer rate, and potato yield. Plant Disease 65: 575-577.

Macy, P. 1936. The quantitative mineral nutrient requirements of plants. Plant Physiology 11: 749-764.

Mardanov, A., A. Samedovam, and T. Shirvany. 1998. Root-shoot relationships in plant adaptation to nitrogen deficiency, p. 147-154. In: Box, J.E.J. (ed.). Root demographics and their efficiencies in sustainable agriculture, grasslands and forest ecosystems. Kluwer Academic Publishers, Boston.

Markovic, V., Z. Ilin, M. Djurovka, and B. Dazic. 2002. Effect of preceeding crop on growth dynamics, yield and quality of carrot. Acta Horticulturae 579: 363-366.

Marschner, H. 1995. Mineral Nutrition of Higher Plants.Second Edition. Academic Press, San Diego.

Matsuyama, N. and A.E. Dimond. 1973. Effect of nitrogenous fertilizer on biochemical processes that could affect lesion size of rice blast. Phytopathology 63: 1202-1203.

Maynard, D.G. and Y.P. Kalra. 1993. Nitrate and exchangeable ammonium nitrogen, p. 25-38. In: Carter, M.R. (ed.). Soil sampling and methods of analysis. Canadian Society of Soil Science, Pinawa, Manitoba.

Maynard, D.N. and G.J. Hochmuth. 1997. Knott's handbook for vegetable growers. Fourth Edition. John Wiley & Sons, Inc., Toronto.

Mazur, S., M. Bartynska, and J. Kucmierz. 1994. Investigations on the influence of differentiated doses of nitrogen fertilizing on the health of carrot roots. Phytopathologica Polonica 7: 7-14.

McCoy, R.E. 1973. Relation of fertility level and fungicide application to incidence of *Cercospora fusimaculans* on St. Augustinegrass. Plant Disease Reporter 57: 33-35.

McDonald, M.R., S. Janse, K. Vander Kooi, and M. Hovius. 2003. Muck Vegetable Cultivar Trial and Research Report. University of Guelph, Muck Crops Research Station. Kettleby, Ontario. 53:97-121.

McGill, W.B. and C.T. Figueiredo. 1993. Total nitrogen, p. 201-211. In: Carter, M.R. (ed.). Soil sampling and methods of analysis. Canadian Society of Soil Science, Pinawa, Manitoba.

McLaren, N.W. 2004. Effect of soil nutrient status on severity of seedling diseases and root rot of sorghum (*Sorghum bicolor*). South African Journal of Plant and Soil 21: 263-265.

McNew, G.L. and E.L. Spencer. 1939. Effect of nitrogen supply of sweet corn on the wilt bacterium. Phytopathology 29: 1051-1067.

Mercier, J. and J. Kuc. 1997. Elicitation of 6-methoxymellein in carrot leaves by *Cercospora carotae*. Journal of the Science of Food and Agriculture 73: 60-62.

Monson, R.K., E.-D. Schulze, M. Freund, and H. Heilmeier. 1994. The influence of nitrogen availability on carbon and nitrogen storage in the biennial *Cirsium vulgare* (Savi) Ten. II. The cost of nitrogen storage. Plant, Cell and Environment 17: 1133-1141.

Montazeri, M. and M.P. Greaves. 2002. Effects of nutrition on desiccation tolerance and virulence of *Colletotrichum truncatum* and *Alternaria alternata* conidia. Biocontrol Science and Technology 12: 173-181.

Neergaard, P. 1945. Danish species of *Alternaria* and *Stemphylium*. Oxford University Press, London.

Nilsson, T. 1979. Yield, storage ability, quality and chemical composition of carrot, cabbage and leek at conventional and organic fertilizing. Acta Horticulturae 93: 209-215.

Nutter, F.W.J. and S.K. Parker. 1997. Fitting disease progress curves using EPIMODEL, p. 24-28. In: Francl, L.J., Neher, D.A. (eds.). Exercises in plant disease epidemiology. APS Press, St. Paul, Minnesota.

Olson, R.V. and C.W. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Science Society of America Journal 48: 583-586.

Ontario Ministry of Agriculture and Food. 2002. Vegetable production recommendations. Publication 363, Queen's Printer for Ontario, Toronto.

Ontario Ministry of Agriculture and Food. 2005. The Nutrient Management Act. http://www.gov.on.ca/OMAFRA/english/agops/index.html.

Osaki, M., M. Matsumoto, T. Shinano, and T. Tadano. 1996. A root-shoot interaction hypothesis for high productivity of root crops. Soil Science and Plant Nutrition 42: 289-301.

Pietola, L. and A.J.M. Smucker. 1998. Fibrous carrot root responses to irrigation and compaction of sandy and organic soils. Plant and Soil 200: 95-105.

Platenius, H. 1934. Chemical changes in carrots during growth. Plant Physiology 9: 671-680.

Prince Edward Island Department of Agriculture, Fisheries, and Aquaculture. 2005. www.gov.pe.ca/af/agweb/index.php3?number=69747&lang=E.

Pryor, B.M. and J.O. Strandberg. 2001. Alternaria leaf blight of carrot. In: Davis, R.M., Raid, R.N. (eds.). Compendium of Umbelliferous Crop Diseases. The American Phytopathological Society Press.

Pryor, B.M., J.O. Strandberg, R.M. Davis, J.J. Nunez, and R.L. Gilbertson. 2002. Survival and persistence of *Alternaria dauci* in carrot cropping systems. Plant Disease 86: 1115-1122.

Reddy, K.R. 1982. Mineralization of nitrogen in organic soils. Soil Science Society of America Journal 46: 561-566.

Reid, J.B. and J.M. English. 2000. Potential yield in carrots (Daucus carota L.): Theory, test, and an application. Annals of Botany 85: 593-605.

Robert, C., M.O. Bancal, and C. Lannou. 2002. Wheat leaf rust uredospore production and carbon and nitrogen export in relation to lesion size and density. Phytopathology 92: 762-768.

Robinson, S.A., A.P. Slade, G.G. Fox, R. Phillips, R.G. Ratcliffe, and G.R. Stewart. 1991. The role of glutamate dehydrogenase in plant nitrogen metabolism. Plant Physiology 95: 509-516.

Rossi, A.M. and D.R. Strong. 1991. Effects of host-plant nitrogen on the preference and performance of laboratory populations of *Carneocephala floridana* (Homoptera: Cecadellidae). Environmental Entomology 20: 1349-1355.

Rotem, J. 1994. The genus *Alternaria*: biology, epidemiology, and pathogenicity. American Phytopathological Society Press, St. Paul.

Rubatzky, V.E., C.F. Quiros, and P.W. Simon. 1999. Carrots and related vegetable *Umbelliferae*. CABI Publishing, New York.

Rühlmann, J. and B. Geyer. 1993. Validation of a simulation model for carbon and nitrogen dynamics in soil in a field trial. Acta Horticulturae 339: 75-84.

Ryan, M.C., R.G. Kachanoski, and R.W. Gillham. 2000. Overwinter soil nitrogen dynamics in seasonally frozen soils. Canadian Journal of Soil Science 80: 541-550.

Salisbury, F.B. and C.W. Ross. 1992. Plant Physiology, 4th Edition. Wadsworth Publishing Company, Belmont, CA.

Salo, T. 1999. N uptake by cabbage, carrot and onion, p. 57-59. Agrifood Quality II: Quality Management of Fruits and Vegetables. Royal Society of Chemistry, Cambridge.

Sanderson, K.R. and J.A. Ivany. 1997. Carrot yield response to nitrogen rate. Journal of Production Agriculture 10: 336-339.

Shepers, J.S., D.D. Francais, and M.T. Thompson. 1989. Automated total nitrogen of soil and plant samples. Communications in Soil Science and Plant Analysis 20: 949-959.

Sheppard, S.C. and T.E. Bates. 1986. Changes in nitrate concentration over winter in three southern Ontario soil profiles. Canadian Journal of Soil Science 66: 537-541.

Simon, P.W. 1992. Genetic improvement of vegetable carotene content. Biotechnology and Nutrition - Proceedings of the Third International Symposium, London. p. 291-300.

Simon, P.W. and J.O. Strandberg. 1998. Diallel analysis of resistance in carrot to *Alternaria* leaf blight. Journal of the American Society for Horticultural Science 123: 412-415.

Soltanpour, P.N. and M.D. Harrison. 1974. Interrelations between nitrogen and phosphorus fertilization and early blight control of potatoes. American Potato Journal 51: 1-7.

Soteros, J.J. 1979. Pathogenicity and control of *Alternaria radicina* and *A. dauci* in carrots. New Zealand Journal of Agricultural Research 22: 191-196.

Statistics Canada. 2004. Fruit and Vegetable Production, http://dsp-psd.pwgsc.gc.ca/Collection-R/Statcan/22-003-XIB/0010422-003-XIB.pdf

Strandberg, J.O. 1987. Isolation, storage, and inoculum production methods for *Alternaria dauci*. Phytopathology 77: 1008-1012.

Strandberg, J.O. 1988. Establishment of Alternaria leaf blight on carrots in controlled environments. Plant Disease 72: 522-526.

Strandberg, J.O. 2001. Monitoring growth and development of carrot on organic soils in Florida. Proceedings of the Florida State Horticultural Society 114: 307-312.

Strandberg, J.O., M.J. Bassett, C.E. Peterson, and R.D. Berger. 1972. Sources of resistance to *Alternaria dauci*. HortScience 7: 345.

Sutton, J. and T. Gillespie. 1979. Weather-Timed Sprays for Carrot Blight Control. Ontario Ministry of Agriculture, Food, and Rural Affairs. FactSheet 79-035.

Tan, C.S., C.F. Drury, W.D. Reynolds, P.H. Groenevelt, and H. Dadfar. 2002. Water and nitrate loss through tiles under a clay loam soil in Ontario after 42 years of consistent fertilization and crop rotation. Agriculture, Ecosystems and Environment 93: 121-130.

Thomas, H.R. 1943. Cercospora blight of carrot. Phytopathology 33: 114-125.

Thorup-Kristensen, K. 1994. The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. Fertilizer Research 37: 227-234.

Thorup-Kristensen, K. 2002. Utilising differences in rooting depth to design vegetable crop rotations with high nitrogen use efficiency (NUE). Acta Horticulturae 571: 249-254.

Thorup-Kristensen, K. and R. van den Boogaard. 1999. Vertical and horizontal development of the root system of carrots following green manure. Plant and Soil 212: 145-153.

Tompkins, D.K., A.T. Wright, and D.B. Fowler. 1992. Foliar disease development in no-till winter wheat: influence of agronomic practices on powdery mildew development. Canadian Journal of Plant Science 72: 965-972.

Tremblay, M.-H.M. and F. Charbonneau. 1993. Plant nutrient composition as a component of crop protection. Acta Horticulturae 339: 85-97.

van Delden, A. and O. Carisse. 1993. Effect of plant age, leaf age and leaf position on infection of carrot leaves by *Cercospora carotae*. Phytoprotection 74: 75-87.

Venter, F. 1979. Nitrate contents in carrots (Daucus carota L.) as influenced by fertilization. Acta Horticulturae 93: 163-171.

Vereecke, M. and D. Van Maercke. 1979. Substractive fertilization experiment on carrots (*Daucus carota* L.) in relation to soil- and leaf analysis, yield and quality. Acta Horticulturae 93: 197-208.

Villagarcia, M.R., W.W. Collins, and C.D.J. Raper. 1998. Nitrate uptake and nitrogen use efficiency of two sweetpotato genotypes during early stages of storage root formation. Journal of the American Society for Horticultural Science 123: 814-820.

Vintal, H., E. Ben-Noon, E. Shlevin, U. Yermiyahu, D. Shtienberg, and A. Dinoor. 1999. Influence of rate of fertilization on Alternaria leaf blight (*Alternaria dauci*) in carrots. Phytoparasitica 27: 193-200.

Vos, J. and P.E.L. van der Putten. 1997. Field observations on nitrogen catch crops. I. Potential and actual growth and nitrogen accumulation in relation to sowing date and crop species. Plant and Soil 195: 299-309.

Vos, J. and P.E.L. van der Putten. 2000. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. I. input and offtake of nitrogen, phosphorus and potassium. Nutrient Cycling in Agroecosystems 56: 87-97.

Vos, J. and P.E.L. van der Putten. 2004. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. II. effect of catch

crops on nitrate leaching in autumn and winter. Nutrient Cycling in Agroecosystems 70: 23-31.

Vos, J., P.E.L. van der Putten, M.H. Hussein, A.M. van Dam, and P.A. Leffelaar. 1998. Field observations on nitrogen catch crops. Plant and Soil 201: 149-155.

Vos, J.G.M. and H.D. Frinking. 1997. Nitrogen fertilization as a component of integrated crop management of hot pepper (*Capsicum spp*.) under tropical lowland conditions. International Journal of Pest Management 43: 1-10.

Warncke, D.D. 1996. Soil and plant tissue testing for nitrogen management in carrots. Communications in Soil Science and Plant Analysis 27: 597-605.

Westerveld, S.M. 2002. Nitrogen management of cabbage, onions, and carrots as part of an integrated crop management program in Ontario. M.Sc. Thesis, University of Guelph, Guelph, Ontario, Canada.

Westerveld, S.M., M.R. McDonald, C.D. Scott-Dupree, and A.W. McKeown. 2002. The effect of nitrogen on insect and disease pests of onions, carrots, and cabbage. Journal of Vegetable Crop Production 8: 87-99.

Westerveld, S.M., M.R. McDonald, C.D. Scott-Dupree, and A.W. McKeown. 2005. Assessment of a nitrate meter for nitrogen tests in mineral and organic soils. Journal of Vegetable Science in press.

Westerveld, S.M., A.W. McKeown, C.D. Scott-Dupree, and M.R. McDonald. 2003a. Chlorophyll and nitrate meters as nitrogen monitoring tools for selected vegetables in Southern Ontario. Acta Horticulturae 627: 259-266.

Westerveld, S.M., A.W. McKeown, C.D. Scott-Dupree, and M.R. McDonald. 2003b. How well do critical nitrogen concentrations work for cabbage, carrot, and onion crops? HortScience 38: 1122-1128.

White, J.M. and J.O. Strandberg. 1978. Early root growth of carrots in organic soil. Journal of the American Society for Horticultural Science 103: 344-347.

White, J.M., J.O. Strandberg, and R.L. Brown. 1983. Influence of fertilizer on Alternaria leaf blight and yield of carrots grown in muck. Proceedings of the Soil and Crop Science Society of Florida 42: 153-157.

Wiebe, H.J. 1987. Effects of plant densities and nitrogen supply on yield harvest date and quality of carrots. Acta Horticulturae 198: 191-198.

Yiridoe, E.K., R.P. Voroney, and A. Weersink. 1997. Impact of alternative farm management practices on nitrogen pollution of groundwater: evaluation and application of CENTURY model. Journal of Environmental Quality 26: 1255-1263.

Zebarth, B.J., S. Freyman, and C.G. Kowalenko. 1991. Influence of nitrogen fertilization on cabbage yield, head nitrogen content and extractable soil inorganic nitrogen at harvest. Canadian Journal of Plant Science 71: 1275-1280.

Zebarth, B.J., Y. Leclerc, and G. Moreau. 2004. Rate and timing of nitrogen fertilization of Russet Burbank potato: nitrogen use efficiency. Canadian Journal of Plant Science 84: 845-854.

Zebarth, B.J., Y. Leclerc, G. Moreau, R. Gareau, and P.H. Milburn. 2003. Soil inorganic nitrogen content in commercial potato field in New Brunswick. Canadian Journal of Soil Science 83: 425-429.

Appendix 1. Effects of N sequence and timing over 3-years on yield, quality, and stand of carrots at harvest.

Materials and Methods

Additional treatments were included in the three-year plots discussed in Chapter 2 to identify the effectiveness of different timings of N and to determine how the response of carrots to N changes depending on the N applied in the previous year. These treatments are summarized in Table A1.1. Only yield and quality data were collected from these additional treatments as described for the N rate treatments in Chapter 2. For the presentation of results, the N rate treatments exhibiting the maximum or minimum of the variable presented were included for comparison.

Data were analysed using the linear model section of Statistix V.4.1. A type I error rate of 0.05 was set for all statistical tests.

Results

There were no differences between the cultivars in their response to treatment and combined data from the two cultivars are reported. The comparisons between the two cultivars were similar to the responses in the N rate portion of the trial presented in Chapter 2 and are not reported. Total yield of carrots in the additional N treatments was not improved over the N rate exhibiting the maximum total yield of carrots for each year on either soil type (Table A1.2). There were no significant effects of N sequence on yield on organic soil (Table A1.2). On mineral soil in 2003 the carrots receiving the recommended N rate either preplant or sidedressed at the end of July had higher total

yields than the treatments receiving either no N for two consecutive years, or 50% of the recommended rate sidedressed at the end of July (Table A1.2). In 2004 on mineral soil, the carrots receiving no N in 2004 had lower yields than the carrots receiving N in most cases (Table A1.2). The highest yields occurred in the carrots receiving the recommended N rate either preplant or applied at the end of July.

Marketable yield results paralleled total yield results in all cases on both soil types (Table A1.3). Weight per root was higher in 2003 and 2004 in the N rate treatment exhibiting the highest weight per root for each year than in any of the additional N sequence and timing treatments on mineral soil (Table A1.4). There was no effect of N treatment on weight per root on organic soil.

The treatments with the lowest levels of preplant N exhibited the densest stand at harvest on mineral soil in 2003 and 2004 (Table A1.5). There were no effects of treatment on stand at harvest on organic soil in either year (Table A1.5).

The distribution of carrots in the two size grades reflected differences in weight per root on mineral soil (Tables A1.6 and A1.7). The carrots given preplant N in 2004 had a much higher proportion of roots in the large grade than the carrots receiving the same N rate all sidedressed in the end of July (Table A1.6). There were no effects of treatment on the distribution of roots in the size grades on organic soil (Tables A1.6 and A1.7).

On mineral soil in 2003 and organic soil in 2004 there were no effects of N treatment on the proportion of roots in the cull grade (Table A1.8). On organic soil in 2003 there were more culls in the recommended rate preplant treatment and the N rate treatment exhibiting the maximum proportion of culls than the treatment with no N for

two consecutive years (Table A1.8). In addition, the carrots receiving the recommended rate preplant had more culls than the carrots receiving the recommended rate all sidedressed at the end of July (Table A1.8). On mineral soil in 2004 the highest proportion of carrots in the cull category occurred in the N rate treatment with the maximum number of culls.

Discussion and Conclusions

One of the preplant N rate treatments always produced higher yields than any of the additional treatments. However, there were a few cases where sidedress N reduced the number of culls at harvest. Overall, preplant N appears to be much more important for the determination of yield potential, and late sidedress N has little effect on carrot yield or quality. The N applied in late sidedress treatments was probably too late in the season, and may not have leached into the root zone because of low rainfall during the time of sidedress application. A properly timed irrigation could have improved the effectiveness of sidedress application, but irrigation was not available for these experimental plots.

Table A1.2. Additional treatments applied in 3-year plots on mineral and organic soil.

Soil Type	Treatment Name	2002		2003		2004	
		N applied	Timing	N applied	Timing	N applied	Timing
Mineral	0/100/0	0	--	100	preplant	0	--
	0/0/100	0	--	0	--	100	preplant
	0/100/100	0	--	100	preplant	100	preplant
	100/100/0	100	preplant	100	preplant	0	--
	0/50L/50L	0	--	50	end of July	50	end of July
	0/100L/100L	0	--	100	end of July	100	end of July
	100/100L/0	100	preplant	100	end of July	0	--
Organic	0/0/100	0	--	0	--	100	preplant
	0/100/0	0	--	100	preplant	0	--
	0/100L/100/L	0	--	100	end of July	100	end of July

Table A1.2. Effect of nitrogen (N) application sequence over three years and N timing on total yield of carrots grown on organic and mineral soils (average of two cultivars).

Treatment Name Yr1/Yr2/Yr3	Total Yield ($t \cdot ha^{-1}$)			
	2003		2004	
	Mineral	Organic	Mineral	Organic
0/100/0	54.2 d[z]	76.4 a	37.7 ab	67.0 a
0/0/100	38.3 a	78.9 a	51.9 c	71.4 a
0/100/100	50.3 cd	--	48.5 bc	--
100/100/0	52.3 cd	--	33.9 a	--
0/50L/50L	42.3 ab	--	40.8 ab	--
0/100L/100L	51.7 cd	74.1 a	48.4 bc	68.0 a
100/100L/0	47.8 bc	--	44.8 bc	--
Maximum yield[y]	54.7 d	79.1 a	50.9 bc	72.7 a

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

[y] Nitrogen rate treatment with the maximum total yield for the respective soil type and year.

Table A1.3. Effect of nitrogen (N) application sequence over three years and N timing on marketable yield of carrots grown on organic and mineral soils (average of two cultivars).

Treatment Name	Marketable Yield ($t \cdot ha^{-1}$)			
	2003		2004	
	Mineral	Organic	Mineral	Organic
0/100/0	47.6 c[z]	76.4 a	34.9 cd	59.1 a
0/0/100	31.8 a	79.9 a	47.3 d	60.8 a
0/100/100	44.6 c	--	43.4 cd	--
100/100/0	45.7 c	--	30.5 a	--
0/50L/50L	36.5 ab	--	38.1 bc	--
0/100L/100L	43.8 c	74.1 a	44.0 cd	58.2 a
100/100L/0	42.1 bc	--	40.9 b-d	--
Maximum yield[y]	49.4 c	79.1 a	46.2 cd	63.9 a

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.
[y] Nitrogen rate treatment with the maximum marketable yield for the respective soil type and year.

Table A1.4. Effect of nitrogen (N) application sequence over three years and N timing on weight per root of carrots grown on organic and mineral soils (average of two cultivars).

Treatment Name	Weight per Root (g)			
	2003		2004	
	Mineral	Organic	Mineral	Organic
0/100/0	78.0 b[z]	144.7 a	66.2 a	122.9 a
0/0/100	47.1 a	131.7 a	122.7 b	134.1 ab
0/100/100	71.3 b	--	102.6 ab	--
100/100/0	74.3 b	--	60.4 a	--
0/50L/50L	55.1 ab	--	67.8 a	--
0/100L/100L	66.6 b	126.5 a	80.2 ab	121.0 a
100/100L/0	67.8 b	--	87.6 ab	--
Maximum yield[y]	125.9 c	137.6 a	195.5 c	146.8 b

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.
[y] Nitrogen rate treatment with the maximum weight per root for the respective soil type and year.

Table A1.5. Effect of nitrogen (N) application sequence over three years and N timing on stand at harvest of carrots grown on organic and mineral soils (average of two cultivars).

Treatment Name	Stand at Harvest (plants·m^{-1})			
	2003		2004	
	Mineral	Organic	Mineral	Organic
0/100/0	141.6 a[z]	47.4 a	49.9 ab	47.0 a
0/0/100	163.9 b	52.6 a	40.7 a	45.9 a
0/100/100	145.4 a	--	42.3 ab	--
100/100/0	143.0 a	--	49.1 ab	--
0/50L/50L	159.3 ab	--	52.4 b	--
0/100L/100L	156.8 ab	50.6 a	52.4 b	49.2 a
100/100L/0	145.1 a	--	45.2 ab	--
Maximum yield[y]	148.2 ab	55.7 a	48.4 ab	48.3 a

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.
[y] Nitrogen rate treatment with the maximum stand at harvest for the respective soil type and year.

Table A1.6. Effect of nitrogen (N) application sequence over three years and N timing on the proportion of storage root > 4.4 cm diameter of carrots grown on organic and mineral soils (average of two cultivars).

Treatment Name	Proportion of Roots > 4.4 cm (%)			
	2003		2004	
	Mineral	Organic	Mineral	Organic
0/100/0	7.5 b[z]	34.4 a	4.1 a	26.7 a
0/0/100	1.4 a	31.9 a	23.6 b	26.4 a
0/100/100	3.7 ab	--	16.7 a	--
100/100/0	4.7 ab	--	3.6 a	--
0/50L/50L	1.8 a	--	4.0 a	--
0/100L/100L	3.2 ab	28.6 a	6.7 a	24.3 a
100/100L/0	4.7 ab	--	9.7 a	--
Maximum yield[y]	22.0 c	32.3 a	55.8 c	31.7 a

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.
[y] Nitrogen rate treatment with the maximum proportion of roots > 4.4 cm diameter for the respective soil type and year.

Table A1.7. Effect of nitrogen (N) application sequence over three years and N timing on the proportion of storage roots 2.0 – 4.4 cm diameter of carrots grown on organic and mineral soils (average of two cultivars).

Treatment Name	Proportion of Roots 2.0 – 4.4 cm (%)			
	2003		2004	
	Mineral	Organic	Mineral	Organic
0/100/0	80.0 a[z]	55.9 a	88.6 c	61.7 a
0/0/100	81.5 a	63.6 a	67.6 a	58.9 a
0/100/100	85.0 a	--	72.8 ab	--
100/100/0	82.4 a	--	86.4 c	--
0/50L/50L	82.8 a	--	89.1 c	--
0/100L/100L	82.0 a	66.0 a	84.2 c	61.2 a
100/100L/0	83.4 a	--	81.5 bc	--
Maximum yield[y]	84.5 a	68.0 a	90.6 c	60.9 a

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.
[y] Nitrogen rate treatment with the maximum proportion of roots 2.0 – 4.4 cm diameter for the respective soil type and year.

Table A1.8. Effect of nitrogen (N) application sequence over three years and N timing on the proportion of storage roots that were culls of carrots grown on organic and mineral soils (average of two cultivars).

Treatment Name	Proportion of Roots Culls (%)			
	2003		2004	
	Mineral	Organic	Mineral	Organic
0/100/0	12.5 a[z]	9.7 c	7.2 a	11.6 a
0/0/100	17.1 a	4.6 a	8.9 ab	14.7 a
0/100/100	11.3 a	--	10.6 ab	--
100/100/0	12.9 a	--	10.0 ab	--
0/50L/50L	15.4 a	--	6.9 a	--
0/100L/100L	14.8 a	5.4 ab	9.1 ab	14.5 a
100/100L/0	11.9 a	--	8.8 ab	--
Maximum yield[y]	13.6 a	7.5 bc	11.8 b	13.3 a

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.
[y] Nitrogen rate treatment with the maximum proportion of roots that were culls for the respective soil type and year.

Appendix 2. Additional Data Tables for Chapter 2.

Table A2.1. Carrot stand in the seedling stage of two carrot cultivars grown on mineral and organic soil in 2004.

Cultivar	Stand (plants·m^{-1})				
	Mineral Soil			Organic Soil	
	Jun 11 Live	Jun 11 Dead[z]	Jun 22 Live	Jun 17 Live	Jun 11 Dead[z]
Idaho	43.8 b[y]	2.5 a	41.6 b	48.9 a	0.6 a
Fontana	35.1 a	2.1 a	32.3 a	46.6 a	0.6 a

[z] Plants visible but dead at the time of assessment.

[y] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.2. Effect of annual and alternating nitrogen (N) application rate and cultivar on marketable yield of carrots grown on mineral and organic soil for three years (N rate data represent the average of two cultivars).

N rate (% of recommended)[z]/ Cultivar		Marketable Yield ($t \cdot ha^{-1}$)					
		2002	2003		2004		3-YR Mean[x]
			Annual[y]	Alter-nating[y]	Annual	Alter-nating	
Mineral Soil							
0		44.4	31.3[w]	31.3	36.5[w]	36.5	37.4
50		43.0	41.0	33.8	43.4	48.1	42.5
100		48.8	45.5	34.2	46.2	49.3	46.8
150		36.1	49.3	40.8	42.0	40.4	42.5
200		38.6	48.5	41.0	28.3	34.0	38.5
Mean		42.2	43.1	36.2	39.3	41.7	41.5
Significance	L	NS	***	*	NS	NS	NS
	Q	NS	NS	NS	***	***	***
	R^2	--	0.62	0.25	0.60	0.63	0.54
Idaho		41.6 a[v]	41.2 a	36.1 a	41.7 b	41.5 a	41.5 a
Fontana		42.7 a	43.4 a	36.4 a	34.1 a	39.0 a	40.1 a
Organic Soil							
0		92.0	75.6	75.6	63.9	63.9	77.2
50		93.3	74.2	76.0	63.5	62.8	77.0
100		91.5	75.4	72.1	61.1	61.1	76.0
150		89.7	69.0	73.8	62.7	60.8	73.8
200		88.0	70.4	75.3	62.5	61.3	73.6
Mean		90.9	72.9	74.6	62.7	62.0	75.5
Significance	L	NS	NS	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--
Idaho		87.2 a	72.0 a	76.1 a	64.5 a	66.6 b	74.6 a
Fontana		94.6 b	73.8 a	73.0 a	61.0 a	57.4 a	76.5 a

[z] Recommended rates: organic soil = 60 $kg \cdot ha^{-1}$ N preplant, mineral soil = 110 $kg \cdot ha^{-1}$ split 66% preplant/33% sidedress.

[y] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.

[x] Average of annual fertilizer sections only.

[w] One outlier removed due to localized flooding.

[v] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

NS,*,**,*** Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table A2.3. Effect of annual or alternating nitrogen (N) application rate and cultivar on weight per root of carrots grown on mineral and organic soil for three years (N rate data represent the average of two cultivars).

N rate (% of recommended)[z] / Cultivar		Weight per Root (g)					
		2002	2003		2004		3-YR Mean[x]
			Annual[y]	Alter-nating[y]	Annual	Alter-nating	
Mineral Soil							
0		120.7	48.9	48.9	69.5[w]	69.5	79.7
50		97.4	69.1	51.0	89.6	61.9	85.4
100		116.9	80.0	53.3	131.4	91.1	109.4
150		145.3	95.8	65.4	145.2	77.6	128.8
200		142.8	125.9	73.1	166.1	114.7	144.9
Mean		124.6	83.9	58.3	120.4	83.0	109.6
Sign.	L	NS	***	**	***	*	***
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	0.58	0.35	0.79	0.23	0.53
Idaho		110.9 a[v]	73.9 a	55.1 a	113.6 a	82.0 a	99.4 a
Fontana		138.4 b	94.0 b	61.6 a	147.0 b	89.1 a	126.5 b
Organic Soil							
0		179.6	132.3	132.3	132.9	132.9	148.5
50		158.2	123.9	125.5	146.8	130.9	140.3
100		161.8	131.1	135.2	136.1	148.6	145.1
150		164.3	137.6	127.8	142.9	128.2	145.8
200		174.9	135.2	129.9	128.2	138.6	147.8
Mean		167.8	132.0	130.1	137.4	135.8	145.5
Sign.	L	NS	NS	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--
Idaho		144.9 a	121.3 a	125.2 a	143.2 b	138.0 a	136.5 a
Fontana		190.6 b	142.8 b	135.2 a	131.6 a	133.6 a	155.0 b

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.

[x] Average of annual fertilizer sections only.

[w] One outlier removed for statistical analysis and for reported means and one outlier removed due to localized flooding.

[v] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table A2.4. Stand at harvest of two carrot cultivars grown on mineral and organic soil continuously for three years.

Cultivar	Stand at Harvest (roots·m of row^{-1})					
	2002	2003		2004		3-year Mean[y]
		Annual[z]	Alter-nating[z]	Annual	Alter-nating	
Mineral Soil						
Idaho	39.0 b[x]	61.5 b	67.7 b	38.5 b	34.6 a	46.4 b
Fontana	31.0 a	47.9 a	59.7 a	29.7 a	31.8 a	36.2 a
Organic Soil						
Idaho	56.2 b	55.6 b	55.7 b	46.3 a	49.7 b	52.7 b
Fontana	44.5 a	47.6 a	49.7 a	44.7 a	42.2 a	45.6 a

[z] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.

[y] Average of annual fertilizer sections only.

[x] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.5. Effect of annual or alternating nitrogen (N) application rate and cultivar on the percent by weight of roots larger than 4.4 cm diameter of carrots grown on mineral and organic soil for three years (N rate data represent the average of two cultivars).

N rate (% of recommended)[z]/ Cultivar		Proportion > 4.4 cm diameter (%)					
		2002	2003		2004		3-YR Mean[x]
			Annual[y]	Alter-nating[y]	Annual	Alter-nating	
Mineral Soil							
0		19.5	1.9[w]	1.9	3.4	3.4	8.3
50		10.5	6.1	2.6	10.9	13.3	9.2
100		16.9	10.5	2.2	34.1	41.7	20.5
150		26.3	12.2	6.8	34.2	34.8	24.2
200		25.2	15.0	4.9	55.8	53.3	32.0
Mean		19.7	9.1	3.7	27.7	29.3	18.8
Significance	L	NS	**	NS	***	**	***
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	0.34	--	0.77	0.48	0.48
Idaho		12.2 a[v]	4.8 a	2.3 a	19.9 a	25.5 a	12.3 a
Fontana		27.1 b	16.3 b	5.1 b	37.0 b	35.1 b	26.8 b
Organic Soil							
0		35.8	32.3	32.3	30.4	30.4	32.8
50		32.4	26.1	26.8	29.4	26.8	29.3
100		34.3	31.7	29.4	28.9	36.7	31.6
150		33.7	32.3	26.7	31.7	26.8	32.6
200		34.4	31.6	29.8	26.3	29.7	30.8
Mean		34.1	30.8	29.0	29.3	30.1	31.4
Significance	L	NS	NS	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--
Idaho		21.8 a	21.5 a	22.5 a	28.0 a	27.8 a	23.7 a
Fontana		46.4 b	40.1 b	35.5 b	30.8 a	32.3 a	39.1 b

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.

[x] Average of annual fertilizer sections only.

[w] One outlier removed for the analysis.

[v] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table A2.6. Effect of annual or alternating nitrogen (N) application rate and cultivar on the percent by weight of roots between 2.0 and 4.4 cm diameter of carrots grown on mineral and organic soil for three years (N rate data represent the average of two cultivars).

N rate (% of recommended)[z]/ Cultivar		Proportion 2.0 – 4.4 cm diameter (%)					
		2002	2003		2004		3-YR Mean[x]
			Annual[y]	Alter-nating[y]	Annual	Alter-nating	
Mineral Soil							
0		74.1	84.5	84.5	90.6[w]	90.6[w]	83.1
50		84.3	80.3	83.1	81.2	79.6	81.9
100		76.3	79.0	82.2	56.5	49.6	70.6
150		64.9	78.1	79.1	54.6	48.8	65.9
200		64.0	65.3	82.2	35.0	14.0	54.8
Mean		72.7	77.4	82.2	63.6	56.5	71.3
Significance	L	NS	*	NS	***	***	**
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	0.31	--	0.79	0.79	0.37
Idaho		78.5 b[v]	79.2 a	81.7 a	72.0 b	64.3 b	76.6 b
Fontana		66.9 a	75.7 a	82.7 a	52.7 a	52.1 a	65.1 a
Organic Soil							
0		60.4	63.7	63.7	58.6	58.6	60.9
50		63.8	68.0	68.0	57.6	64.1	63.1
100		61.6	63.6	65.1	59.0	48.7	61.4
150		61.3	60.2	68.5	55.1	57.2	58.9
200		61.1	62.5	66.1	60.9	55.3	61.5
Mean		61.6	63.6	66.3	58.2	56.8	61.1
Significance	L	NS	NS	NS	NS	NS	NS
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	--	--	--
Idaho		73.1 b	71.9 b	73.1 b	57.8 a	57.8 a	67.6 b
Fontana		50.2 a	55.4 a	59.4 a	58.7 a	55.7 a	54.8 a

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.

[x] Average of annual fertilizer sections only.

[w] One outlier removed for the analysis.

[v] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table A2.7. Effect of annual or alternating nitrogen (N) application rate and cultivar on the percent by weight of cull roots of carrots grown on mineral and organic soil for three years (N rate data represent the average of two cultivars).

N rate (% of recommended)[z]/ Cultivar		Proportion culls (%)					
		2002	2003		2004		3-YR Mean[x]
			Annual[y]	Alter-nating[y]	Annual	Alter-nating	
Mineral Soil							
0		6.6	13.6	13.6	6.0[w]	6.0	8.7
50		5.2	13.5	14.4	7.9	7.1	8.9
100		6.9	10.5	15.6	9.4	8.7	8.9
150		9.0	9.6	14.1	11.2	16.4	9.9
200		10.9	12.7	12.9	11.5	14.4	11.7
Mean		7.7	12.0	14.1	9.2	10.5	9.6
Significance	L	NS	NS	NS	***	***	*
	Q	NS	NS	NS	NS	NS	NS
	R^2	--	--	--	0.72	0.54	0.21
Idaho		9.3 a[v]	15.9 b	16.1 b	8.2 a	10.2 a	11.1 b
Fontana		6.0 a	8.1 a	12.2 a	10.3 a	12.8 a	8.2 a
Organic Soil							
0		3.9	4.0	4.0	10.9	10.9	6.3
50		3.8	5.9	5.1	13.0	9.2	7.6
100		4.1	4.7	5.5	12.1	14.6	7.0
150		5.1	7.5	4.8	13.3	16.0	8.6
200		4.6	5.9	4.2	12.8	15.0	7.8
Mean		4.3	5.6	4.7	12.4	13.1	7.4
Significance	L	NS		NS	NS	*	NS
	Q	NS		NS	NS	NS	NS
	R^2	--		--	--	0.31	--
Idaho		5.2 b	6.7 b	4.4 a	14.3 a	143.6 a	8.7 b
Fontana		3.4 a	4.5 a	5.0 a	10.5 a	119.3 a	6.1 a

[z] Recommended rates: organic soil = 60 kg·ha^{-1} N preplant, mineral soil = 110 kg·ha^{-1} split 66% preplant/33% sidedress.

[y] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.

[x] Average of annual fertilizer sections only.

[w] one outlier removed for reported means and statistical analysis and one data point removed due to localized flooding.

[v] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table A2.8. Total yield of two carrot cultivars grown on mineral and organic soil continuously for three years.

Cultivar	Total Yield ($t \cdot ha^{-1}$)					
	2002	2003		2004		3-YR Mean[y]
		Annual[z]	Alter-nating[z]	Annual	Alter-nating	
Mineral Soil						
Idaho	45.9 a[x]	48.7 a	42.8 a	45.3 b	46.1 a	46.6 b
Fontana	45.6 a	47.2 a	41.2 a	38.0 a	44.6 a	43.6 a
Organic Soil						
Idaho	91.9 a	77.2 a	79.6 a	75.1 b	77.9 b	81.4 a
Fontana	97.9 b	77.2 a	76.9 a	68.0 a	65.1 a	81.0 a

[z] Annual = fertilized for all three years; Alternating = fertilized in 2002 and 2004 only, and 2003 results are based on 2002 N application.
[y] Average of annual fertilizer sections only.
[x] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.9. Effect of foliar nitrogen (N) and N timing on marketable yield of carrots grown on mineral and muck soil in 2002, 2003, and 2004 in separate locations each year (average of two cultivars).

Treatment (% of Recommended)		Marketable Yield ($t \cdot ha^{-1}$)					
Pre-plant N	Addi-tional[z]	Mineral Soil			Organic Soil		
		2002	2003	2004	2002	2003	2004
0	0	36.1 a[y]	38.1 a	44.1 a	92.1 a	100.1 a	72.0 a
0	Foliar	40.0 a	43.7 b	41.2 a	88.9 a	96.8 a	88.3 b
0	Foliar-S	--	39.5 ab	44.3 a	--	96.9 a	79.8 ab
50	Foliar	40.9 a	54.5 c	42.8 a	88.3 a	99.5 a	89.7 b
100	Foliar	35.2 a	63.5 de	43.1 a	89.8 a	97.3 a	79.9 ab
50	50	39.0 a	59.9 d	42.3 a	87.4 a	100.4 a	76.3 a
0	50	--	--	--	--	--	77.9 a
0	100	36.0 a	60.0 d	42.4 a	92.5 a	--	75.9 a
0	200	--	67.8 e	41.6 a	--	--	--

[z] Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$N as urea (with AGRAL 90 surfactant in 2003 and 2004) beginning when canopy is 75% closed; Foliar-S = same as Foliar+surf. without surfactant.
[y] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.10. Effect of foliar nitrogen (N) and N timing on weight per root of carrots grown on mineral and muck soil in 2002, 2003, and 2004 in separate locations each year (average of two cultivars).

Treatment (% of Recommended)		Weight per Root (g)					
Pre-plant N	Addi-tional[z]	Mineral Soil			Organic Soil		
		2002	2003	2004	2002	2003	2004
0	0	166.3 a[y]	85.3 ab	90.5 ab	156.1 a	159.3 a	124.8 ab
0	Foliar	178.5 ab	76.4 a	91.6 a-c	143.8 a	153.3 a	138.3 bc
0	Foliar-S	--	79.0 ab	91.4 a-c	--	152.9 a	124.1 a
50	Foliar	190.3 a-c	104.0 a-c	99.0 b-d	154.5 a	156.0 a	159.4 d
100	Foliar	238.9 d	123.1 c	104.4 d	152.7 a	164.4 a	141.3 c
50	50	202.6 bc	112.3 bc	99.7 cd	154.8 a	166.3 a	119.4 a
0	50	--	--	--	--	--	138.5 bc
0	100	207.0 c	135.3 c	87.6 a	159.9 a	--	127.1 ab
0	200	--	131.0 c	84.3 a	--	--	--

[z] Foliar = biweekly foliar sprays of 2 kg·ha^{-1} N as urea (with AGRAL 90 surfactant added in 2003 and 2004) beginning when canopy is 75% closed; Foliar-S = same as Foliar treatment without surfactant.
[y] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.11. Effect of foliar nitrogen (N) and N timing on stand at harvest of carrots grown on mineral and muck soil in 2002, 2003, and 2004 in separate locations each year (average of two cultivars).

Treatment (% of Recommended)		Stand at Harvest (plants·m^{-1})					
Pre-plant N	Addi-tional[z]	Mineral Soil			Organic Soil		
		2002	2003	2004	2002	2003	2004
0	0	22.0 a[y]	48.8 a	52.6 a	62.7 a	54.4 a	66.5 a
0	Foliar	22.0 a	58.2 a	48.5 a	64.9 a	54.6 a	69.0 a
0	Foliar-S	--	55.0 a	51.6 a	--	54.8 a	70.9 a
50	Foliar	20.7 a	57.9 a	46.9 a	60.6 a	55.0 a	64.9 a
100	Foliar	16.5 a	53.4 a	45.2 a	62.6 a	51.5 a	65.8 a
50	50	19.7 a	54.0 a	45.2 a	60.5 a	52.2 a	72.8 a
0	50	--	--	--	--	--	64.8 a
0	100	19.0 a	47.9 a	51.1 a	61.2 a	--	69.0 a
0	200	--	54.4 a	52.2 a	--	--	--

[z] Foliar = biweekly foliar sprays of 2 kg·ha^{-1} N as urea (with AGRAL 90 surfactant added in 2003 and 2004) beginning when canopy is 75% closed; Foliar-S = same as Foliar treatment without surfactant.
[y] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.12. Effect of foliar nitrogen (N) and N timing on percent by weight of storage roots > 4.4 cm diameter of carrots grown on mineral and muck soil in 2002, 2003, and 2004 in separate locations each year (average of two cultivars).

Treatment (% of Recommended)		Proportion of roots >4.4 cm (%)					
Pre-	Addi-	Mineral Soil			Organic Soil		
plant N	tional[z]	2002	2003	2004	2002	2003	2004
0	0	53.0 a[y]	17.7 a-c	7.5 a	28.7 a	42.4 b	29.7 a
0	Foliar	48.9 a	9.5 a	6.8 a	23.8 a	40.7 ab	38.6 bc
0	Foliar-S	--	14.3 ab	6.3 a	--	36.5 a	31.0 ab
50	Foliar	55.0 a	25.0 b-d	8.6 a	31.5 a	44.0 b	44.5 c
100	Foliar	61.8 a	31.4 cd	11.6 a	25.1 a	45.7 b	40.4 c
50	50	58.0 a	28.2 b-d	12.3 a	27.7 a	45.0 b	29.4 a
0	50	--	--	--	--	--	36.6 a-c
0	100	58.2 a	28.5 b-d	8.2 a	30.9 a	--	31.7 ab
0	200	--	34.3 d	8.2 a	--	--	--

[z] Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea (with AGRAL 90 surfactant added in 2003 and 2004) beginning when canopy is 75% closed; Foliar-S = same as Foliar treatment without surfactant.
[y] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.13. Effect of foliar nitrogen (N) and N timing on percent of storage roots by weight between 2.0 and 4.4 cm diameter of carrots grown on mineral and muck soil in 2002, 2003, and 2004 in separate locations each year (average of two cultivars).

Treatment (% of Recommended)		Proportion of Roots 2.0 – 4.4 cm (%)					
Pre-	Addi-	Mineral Soil			Organic Soil		
plant N	tional[z]	2002	2003	2004	2002	2003	2004
0	0	33.8 bc[y]	64.8 cd	85.6 a	68.9 a	52.6 a	57.8 c
0	Foliar	40.4 c	75.0 d	86.6 a	73.3 a	51.2 a	54.1 bc
0	Foliar-S	--	62.0 b-d	88.0 a	--	54.7 a	60.9 c
50	Foliar	35.1 bc	60.9 b-d	85.7 a	63.4 a	49.4 a	42.7 a
100	Foliar	23.0 a	50.9 a-c	81.1 a	70.7 a	49.1 a	46.4 ab
50	50	25.8 ab	50.1 ab	84.6 a	68.3 a	48.3 a	59.1 c
0	50	--	--	--	--	--	52.3 bc
0	100	26.6 ab	54.2 bc	86.5 a	65.3 a	--	56.0 c
0	200	--	37.8 a	87.2 a	--	--	--

[z] Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea (with AGRAL 90 surfactant added in 2003 and 2004) beginning when canopy is 75% closed; Foliar-S = same as Foliar treatment without surfactant.
[y] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.14. Effect of foliar nitrogen (N) and N timing on percent of storage roots that were culls of carrots grown on mineral and muck soil in 2002, 2003, and 2004 in separate locations each year (average of two cultivars).

Treatment (% of Recommended)		Proportion of Roots Culls (%)					
		Mineral Soil			Organic Soil		
Pre-plant N	Addi-tional[z]	2002	2003	2004	2002	2003	2004
0	0	13.2 a[y]	17.5 ab	17.5 ab	2.4 a	5.0 a	12.5 a
0	Foliar	10.7 a	15.5 a	15.5 a	2.9 a	8.1 a	7.3 a
0	Foliar–S	--	23.7 cd	23.7 cd	--	8.8 a	8.1 a
50	Foliar	9.9 a	14.1 a	14.1 a	5.1 a	6.6 a	12.9 a
100	Foliar	15.2 a	17.7 ab	17.7 ab	4.2 a	5.2 a	13.2 a
50	50	16.2 a	21.7 bc	21.7 bc	4.0 a	6.7 a	11.5 a
0	50	--	--	--	--	--	11.1 a
0	100	15.2 a	17.2 ab	17.2 ab	3.9 a	--	12.3 a
0	200	--	27.9 d	27.9 d	--	--	--

[z] Foliar = biweekly foliar sprays of 2 $kg \cdot ha^{-1}$ N as urea (with AGRAL 90 surfactant added in 2003 and 2004) beginning when canopy is 75% closed; Foliar-S= same as Foliar treatment without surfactant.
[y] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.15. Decrease in weight and marketable roots after six months of cold storage of two carrot cultivars grown on mineral and organic soils.

Cultivar	Weight Loss (%)			Cull Losses (%)			Total Loss (%)		
	2002	2003	2004	2002	2003	2004	2002	2003	2004
Mineral Soil									
Idaho	7.2 b[z]	8.6 b	11.1 a	0.1 a	0.6 a	0.3 a	7.3 a	9.1 a	11.4 a
Fontana	6.0 a	7.0 a	9.1 a	1.0 a	4.3 b	1.6 a	7.0 a	11.4 a	10.7 a
Organic Soil									
Idaho	4.9 b	8.5 a	6.2 b	1.3 a	4.7 a	1.0 a	6.2 a	13.1 a	7.2 a
Fontana	3.6 a	6.8 a	5.1 a	4.5 b	11.3 b	2.5 b	8.1 b	18.1 b	7.5 a

[z] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.
[NS,*,**,***] Nonsignificant or significant at P=0.05, 0.01, and 0.001, respectively. L=Linear; Q=quadratic.

Table A2.16. Dry weight and fibrous root depth of two carrot cultivars grown in silica sand in the greenhouse in 150-cm deep PVC pipes.

Cultivar	Dry Weight (g)			Root Depth	Ratio				
					Top Weight to			Storage Root Weight to	
	Top	Storage Root	Fibrous Root		Storage Root Weight	Fibrous Root Weight	Total Root Weight	Fibrous Root Weight	Root Depth
Idaho	1.59 a[z]	7.25 a	1.53 a	118.4 a	0.22 a	1.08 a	0.16 a	5.73 a	0.43 a
Fontana	0.95 a	5.49 a	1.38 a	102.1 a	0.19 a	0.99 a	0.14 a	6.14 a	0.48 a

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A2.17. Recovery of total nitrogen (N) and ^{15}N in carrot tops and roots following injection of 10% ^{15}N enriched potassium nitrate fertilizer injected at three different depths in 150 cm deep PVC pipes as compared to the number of roots crossing the injection site for two carrot cultivars.

Cultivar	Number of roots crossing injection site	Total N recovered (μg)			^{15}N recovered per root crossing injection site (μg)		
		New Leaves	Old Leaves	Roots	New Leaves	Old Leaves	Roots
Idaho	12.4 a[z]	46.8 a	34.9 a	134.4 a	5.42 a	3.99 a	11.47 a
Fontana	16.9 a	65.7 a	31.2 a	71.6 a	2.89 a	1.38 a	3.17 a

[z] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Appendix 3. Significant Regression Equations for Chapter 2.

Table A3.1. Significant linear and quadratic equations for the effect of nitrogen application rate on yield and nitrogen status variables for carrots grown on organic and mineral soil from 2002 to 2004. Equations are listed in the order of their appearance in Chapter 2.

Year	Soil[z]	Variable	R^2	Intercept	Linear	Quadratic
2004	min.	stand – Jun 11	0.63	51.915	-0.1145	--
2004	min.	dead plants – Jun 11	0.37	0.9983	0.0136	--
2004	min.	stand – Jun 22	0.73	52.843	-0.1469	--
2003	min.	total yield – fertilized	0.60	39.799	0.0914	--
2003	min.	total yield - unfertilized	0.30	36.088	0.0592	--
2004	min.	total yield – fert. (3 yrs)	0.58	38.117	0.2857	-0.00157
2004	min.	total yield – fert. (1 yr)	0.65	39.604	0.2837	-0.00143
3-YR	min.	total yield – 3-yr mean	0.49	40.623	0.1863	-0.00091
2003	min.	mark. yield - fertilized	0.62	34.440	0.0892	--
2003	min.	mark. yield - unfertilized	0.25	30.938	0.0530	--
2004	min.	mark. yield – fert. (3 yrs)	0.60	35.914	0.2406	-0.00138
2004	min.	mark. yield – fert. (1 yr)	0.63	37.603	0.2353	-0.00130
3-YR	min.	mark. yield – 3-yr mean	0.54	37.147	0.1681	-0.00085
2003	min.	weight/root - fertilized	0.58	47.810	0.3612	--
2003	min.	weight/root - unfertilized	0.35	45.785	0.1255	--
2004	min.	weight/root – fert. (3 yrs)	0.79	69.818	0.5015	--
2004	min.	weight/root – fert. (1 yr)	0.23	61.330	0.2122	--
3-YR	min.	weight/root – 3-yr mean	0.53	74.087	0.3527	--
2002	min.	stand-harvest	0.39	36.231	0.1018	-0.00069
2003	min.	stand-harvest - fertilized	0.57	66.875	-0.1217	--
2004	min.	stand-harvest – fert. (3 yrs)	0.80	51.052	-0.1589	--
2004	min.	stand-harvest – fert. (1 yr)	0.62	48.113	-0.1365	--
3-YR	min.	stand-harvest – 3-yr mean	0.75	49.474	0.0273	--
2002	org.	stand-harvest	0.42	52.418	0.0408	-0.00035
2003	min.	% > 4.4 cm - fertilized	0.34	2.628	0.0655	--
2004	min.	% > 4.4 cm – fert. (3 yrs)	0.77	1.756	0.2560	--
2004	min.	% > 4.4 cm – fert. (1 yr)	0.48	4.406	0.2427	--
3-YR	min.	% > 4.4 cm – 3-yr mean	0.48	5.289	0.1399	--
2003	min.	% 2.0-4.4 cm - fertilized	0.31	85.597	-0.0814	--
2004	min.	% 2.0-4.4 cm – fert. (3 yrs)	0.79	91.482	-0.2755	--
2004	min.	% 2.0-4.4 cm – fert. (1 yr)	0.79	93.350	-0.3610	--
3-YR	min.	% 2.0-4.4 cm – 3-yr mean	0.37	85.440	-0.1334	--
2004	min.	% culls – fert. (3 yrs)	0.72	6.309	0.0291	--
2004	min.	% culls – fert. (1 yr)	0.54	5.373	0.0523	--
3-YR	min.	% culls – 3-yr mean	0.21	8.239	0.0142	--
2004	org.	% culls – fert. (1 yr)	0.31	10.148	0.0300	--

Year	Soil[z]	Variable	R^2	Intercept	Linear	Quadratic
2003	min.	cull losses in storage	0.28	2.610	-0.0070	--
2002	min.	sap nitrate-N – early Idaho	0.39	262.0	3.043	--
2002	min.	sap nitrate-N – mid Idaho	0.29	161.2	1.379	--
2002	min.	sap nitrate-N – early Font.	0.37	1090.9	6.804	--
2002	min.	tissue nitrate-N - laboratory	0.49	241.7	5.642	--
2002	min.	tissue total N - laboratory	0.44	0.8206	0.0010	--
2003	min.	sap nitrate-N – early Idaho	0.31	289.7	2.096	--
2003	min.	sap nitrate-N – mid Idaho	0.33	207.7	0.445	--
2003	min.	sap nitrate-N – early Font.	0.42	633.1	3.665	--
2003	min.	sap nitrate-N – mid Font.	0.42	158.9	4.760	--
2003	min.	sap nitrate-N – late Font.	0.63	134.0	1.643	--
2003	min.	tissue nitrate-N - laboratory	0.68	24.816	-2.009	0.0389
2004	min.	sap nitrate-N – early Idaho	0.76	219.5	3.733	--
2004	min.	sap nitrate-N – mid Idaho	0.29	128.2	0.3585	--
2004	min.	sap nitrate-N – early Font.	0.45	332.0	26.751	-0.1000
2004	min.	sap nitrate-N – mid Font.	0.61	103.9	2.116	--
2004	min.	sap nitrate-N – late Font.	0.39	171.9	1.649	--
2004	min.	tissue nitrate-N - laboratory	0.74	32.187	-1.600	0.0238
2004	min.	tissue total N - laboratory	0.58	0.604	0.0016	--
2002	org.	sap nitrate-N – mid Font.	0.24	455.9	2.448	--
2003	org.	sap nitrate-N – late Font.	0.23	291.9	1.127	--
2004	org.	sap nitrate-N – late Idaho	0.43	112.7	-0.1990	0.0036
2004	org.	sap nitrate-N – early Font.	0.30	1159.5	5.883	--
2004	org.	sap nitrate-N – mid Font.	0.36	248.2	2.989	--
2004	org.	sap nitrate-N – late Font.	0.67	181.7	2.517	--
2004	org.	tissue nitrate-N - laboratory	0.61	162.09	-1.936	0.0227
2004	org.	tissue total N - laboratory	0.46	0.865	0.0007	--
2002	min.	soil nitrate-N – early	0.68	10.450	0.512	--
2002	min.	soil nitrate-N – mid	0.76	8.950	0.445	--
2002	min.	soil nitrate-N – late	0.73	9.800	0.362	--
2002	min.	lab soil nitrate-N - mid	0.75	10.613	0.410	--
2002	org.	soil nitrate-N – early	0.63	42.600	0.406	--
2002	org.	soil nitrate-N – mid	0.69	7.600	0.236	--
2002	org.	soil nitrate-N – late	0.36	24.900	0.185	--
2002	org.	lab soil nitrate-N - mid	0.56	77.253	0.698	--
2003	min.	soil nitrate-N – early	0.43	10.750	0.147	--
2003	min.	soil nitrate-N – mid	0.59	0.350	0.302	--
2003	min.	soil nitrate-N – late	0.61	4.600	0.146	--
2003	min.	lab soil nitrate-N - mid	0.62	-14.453	0.541	--
2003	org.	soil nitrate-N – early	0.49	37.100	0.374	--
2003	org.	soil nitrate-N – mid	0.52	25.600	0.391	--
2003	org.	soil nitrate-N – late	0.64	11.600	0.292	--
2003	org.	lab soil nitrate-N - late	0.56	53.620	1.437	--
2004	min.	soil nitrate-N – early	0.75	11.093	0.260	--
2004	min.	soil nitrate-N – mid	0.77	4.600	0.326	--

Year	Soil[z]	Variable	R^2	Intercept	Linear	Quadratic
2004	min.	soil nitrate-N – late	0.75	13.035	-0.084	0.00149
2004	min.	lab soil nitrate-N - mid	0.60	2.550	0.210	--
2004	org.	soil nitrate-N – early	0.68	31.129	0.271	--
2004	org.	soil nitrate-N – mid	0.31	19.647	0.237	--
2004	org.	soil nitrate-N – late	0.54	15.377	0.206	--
2004	org.	lab soil nitrate-N - mid	0.33	5.294	0.089	--
2003	org.	harvest soil total N–top 30	0.58	1.871	0.00123	--
2002	min.	preseed soil NO_3-N–top 30	0.53	2.250	0.0740	--
2004	min.	preseed soil NO_3-N-30-60	0.56	0.389	0.0483	--
2004	min.	harvest soil NO_3-N–top 30	0.63	-4.300	0.305	--
2004	min.	harvest soil NO_3-N-30-60	0.90	1.000	-0.0013	0.000200
2003	org.	preseed soil NO_3-N–top 30	0.22	12.500	0.0380	--
2003	org.	harvest soil total N–top 30	0.56	10.833	0.132	--
2004	org.	preseed soil NO_3-N-30-60	0.61	6.667	0.128	-0.000650
2004	org.	harvest soil NO_3-N–top 30	0.84	4.527	0.00503	0.000284
2003	min.	preseed soil NH_4-N-top 30	0.24	3.650	-0.0060	--
2004	org.	preseed soil NH_4-N-top 30	0.23	4.100	-0.0075	--
2004	org.	harvest soil NH_4-N-top 30	0.23	4.050	-0.0045	--
2004	min.	yield vs. preplant available-N top 30	0.76	23.289	0.4564	-0.00167
2004	min.	yield vs. preplant available-N top 60	0.80	20.915	0.4272	-0.00129
PVC	sand	Top dry weight-Idaho	0.37	-1.798	0.0624	-0.000240
PVC	sand	Stor. root dry weight-Idaho	0.37	-6.208	0.257	-0.00101
PVC	sand	ratio top to stor. root-Idaho	0.20	0.142	0.00065	--
PVC	sand	ratio stor. root to depth-Ida.	0.26	-0.0137	0.00136	-0.000005

[z] min. = mineral soil; org. = organic soil.

Appendix 4. Significant Regression Equations for Chapter 4.

Table A4.1. Significant linear and quadratic equations for the effect of nitrogen application rate on leaf blight variables for carrots grown on organic and mineral soil from 2002 to 2004. Equations are listed in the order of their appearance in Chapter 4.

Year	Soil[z]	Variable	R^2	Intercept	Linear	Quadratic
2002	org.	Alternaria AUDPC	0.41	335.0	-0.731	0.00228
2003	org.	Alternaria AUDPC	0.54	386.9	-0.295	--
2004	org.	Alternaria AUDPC	0.69	433.1	-0.855	0.00238
2002	org.	Cercospora AUDPC	0.63	424.5	-0.277	--
2003	org.	Cercospora AUDPC	0.46	414.9	-0.219	--
2004	org.	Cercospora AUDPC-Idaho	0.62	397.5	-0.396	--
2004	org.	Cercospora AUDPC-Font.	0.47	482.7	-0.215	--
2003	min.	Alternaria AUDPC	0.57	380.5	-0.364	--
2004	min.	Alternaria AUDPC	0.50	416.3	-0.470	--
2003	min.	Cercospora AUDPC	0.66	387.8	-0.481	--
2004	min.	Cercospora AUDPC	0.34	379.4	-0.476	--
2004	org.	Preplant avail.-N top 30 vs. Alt AUDPC	0.74	444.09	-0.623	--
2004	org.	Preplant avail.-N top 60 vs. Alt AUDPC	0.77	452.71	-0.629	--
2004	org.	Preplant avail.-N top 90 vs. Alt AUDPC	0.75	458.35	-0.616	--
2004	org.	Preplant avail.-N top 30 vs. Cerc AUDPC	0.63	453.84	-0.517	--
2004	org.	Preplant avail.-N top 60 vs. Cerc AUDPC	0.62	460.04	-0.511	--
2004	org.	Preplant avail.-N top 90 vs. Cerc AUDPC	0.61	464.95	-0.504	--
2003	org.	Alternaria lesions per leaf	0.30	4.280	-0.00674	--
2004	org.	Alt. lesions per leaf-Idaho	0.31	3.417	-0.00858	--
2004	org.	Alt. lesions per leaf-Font.	0.39	9.228	-0.0795	0.000296
2003	org.	Cercospora lesions per leaf	0.70	24.153	-0.0474	--
2003	min.	Alternaria lesions per leaf	0.36	7.050	-0.0167	--
2004	min.	Alternaria lesions per leaf	0.14	7.242	-0.0160	--
2003	min.	Cercospora lesions per leaf	0.29	25.857	-0.0554	--
2004	min.	Cercospora lesions per leaf	0.15	27.485	-0.0632	--
2002	org.	Live leaves per plant	0.23	3.383	0.0491	--
2003	org.	Live leaves per plant	0.42	4.053	0.00633	--
2003	min.	Live leaves per plant	0.70	2.0200	0.0102	--
2004	min.	Live leaves per plant	0.66	2.873	0.0160	--

[z] min. = mineral soil; org. = organic soil.

Appendix 5. Additional Data Tables for Chapter 4.

Table A5.1. Alternaria and Cercospora leaf blight area under the disease progress curve (AUDPC) for two carrot cultivars grown on mineral and organic soil on the same location for three consecutive years.

Soil	Cultivar	Alternaria AUDPC			Cercospora AUDPC		
		2002	2003	2004	2002	2003	2004
Organic	Idaho	272.9 a[z]	325.9 a	331.2 a	353.0 a	359.2 a	358.0 a
	Fontana	319.3 b	388.9 b	435.6 b	440.7 b	426.9 b	461.2 b
Mineral	Idaho	190.0 a	338.5 a	360.7 a	166.1 a	317.5 a	305.4 a
	Fontana	216.4 b	349.6 a	377.9 b	210.9 b	362.0 b	358.2 b

[z] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.2. Alternaria and Cercospora leaf blight lesions per leaf in mid-September for two carrot cultivars grown on mineral and organic soil on the same location for three consecutive years.

Soil	Cultivar	Alternaria Lesions per Leaf		Cercospora Lesions per Leaf	
		2003	2004	2003	2004
Organic	Idaho	2.8 a[z]	2.6 a	13.6 a	25.9 a
	Fontana	4.4 b	5.7 b	25.2 b	49.5 b
Mineral	Idaho	3.9 a	4.9 a	16.3 a	16.2 a
	Fontana	6.8 b	7.0 a	24.3 b	26.1 b

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.3. Number of live leaves per plant at harvest for two carrot cultivars grown on mineral and organic soil on the same location for three consecutive years.

Soil	Cultivar	Number of Live Leaves per Plant		
		2002	2003	2004
Organic	Idaho	4.2 b[z]	5.3 b	5.8 b
	Fontana	3.4 a	4.1 a	4.7 a
Mineral	Idaho	3.3 b	3.3 a	4.6 a
	Fontana	2.7 a	2.8 a	4.3 a

[z] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.4. Comparison of nitrate-N concentrations of two carrot cultivars grown on organic and mineral soil for three consecutive years.

Year/cultivar	Sap Nitrate-N Concentration ($mg \cdot kg^{-1}$)					
	Organic			Mineral		
	Early	Mid-Season	Late	Early	Mid-Season	Late
2002						
Idaho	1196 a[z]	631 a	82 a	566 a	299 a	193 b
Fontana	1225 a	701 a	291 b	1771 b	520 b	113 a
2003						
Idaho	457 a	285 a	182 a	499 a	296 a	207 a
Fontana	847 b	696 b	405 b	1000 b	635 b	298 b
2004						
Idaho	976 a	246 a	158 a	780 a	164 a	266 a
Fontana	1748 b	547 b	433 b	1505 b	316 b	337 a

[z] Numbers in a column within the same year followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.5. Alternaria and Cercospora leaf blight area under the disease progress curve (AUDPC) for two carrot cultivars grown in foliar spray trials on mineral and organic soil.

Soil Type/	Alternaria AUDPC			Cercospora AUDPC		
Cultivar	2002	2003	2004	2002	2003	2004
Organic						
Idaho	334.7 a[z]	317.7 a	286.3 a	352.1 a	347.2 a	279.1 a
Fontana	365.0 b	365.1 b	341.2 b	434.6 b	375.1 b	335.9 b
Mineral						
Idaho	112.5 a	247.6 a	347.5 a	99.8 a	177.9 a	332.2 a
Fontana	158.6 b	258.4 b	401.7 b	143.9 b	210.9 b	403.0 b

[z] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.6. Alternaria and Cercospora leaf blight lesions per leaf in mid-September for two carrot cultivars grown in foliar spray trials on mineral and organic soil.

Soil Type/	Alternaria Lesions per Leaf		Cercospora Lesions per Leaf	
Cultivar	2003	2004	2003	2004
Organic				
Idaho	2.5 a[z]	3.5 a	9.8 a	16.0 a
Fontana	3.7 b	7.9 b	15.0 b	33.6 b
Mineral				
Idaho	3.9 a	4.1 a	4.6 a	25.4 a
Fontana	6.7 b	8.1 b	8.3 b	59.9 b

[z] Numbers in a column followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.7. Effect of foliar nitrogen (N) application on the number of live leaves per plant at harvest for carrots grown on mineral and organic soil.

Soil Type/ Cultivar	Live Leaves per Plant		
	2002	2003	2004
Organic			
Idaho	4.4 b[z]	5.7 b	4.5 b
Fontana	3.3 a	4.3 a	3.7 a
Mineral			
Idaho	4.6 a	3.1 a	3.1 b
Fontana	4.2 a	2.9 a	1.9 a

[z] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.8. Sap nitrate-N concentrations of two carrot cultivars grown on mineral and organic soil in 2002, 2003, and 2004 in foliar N application trials conducted in separate locations each year.

Cultivar	Sap Nitrate-N Concentrations ($mg \cdot kg^{-1}$)					
	Organic			Mineral		
	Early	Mid-season	Late	Early	Mid-season	Late
2002						
Idaho	1097 a	238 a	68 a	230 a	71 a	172 a
Fontana	1550 b	951 b	282 b	785 b	136 b	215 a
2003						
Idaho	1526 a	408 a	575 a	363 a	202 a	193 a
Fontana	1721 a	864 b	667 a	450 b	216 a	202 a
2004						
Idaho	834 a	183 a	173 a	1049 a	359 a	357 a
Fontana	1295 b	548 b	385 b	1305 b	883 b	738 b

[z] Numbers in a column within the same soil type followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.9. Alternaria leaf blight lesions per leaf, nitrate-N concentration prior to inoculation, and senescence rating prior to inoculation of individual carrot leaves artificially inoculated with Alternaria dauci on two carrot cultivars grown in the greenhouse in silica sand.

Cultivar	Alternaria Leaf Blight Lesions per Leaf	NO_3-N Concentration $mg \cdot kg^{-1}$	Senescence Rating[z]
Idaho	2.55 a[y]	166.2 a	2.79 a
Fontana	5.40 a	142.4 a	2.37 a

[z] Scale: 0 = leaf dark green, 2 = leaf light green, 4 = mild chlorosis, 6 = major chlorosis.
[y] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Table A5.10. Effect of nitrogen (N) application rate on Cercospora leaf blight lesions per leaf, nitrate-N (NO_3-N) concentration prior to inoculation, and senescence rating prior to inoculation of carrots plants grown in silica sand and soil-less mix in the greenhouse and artificially inoculated with *Cercospora carotae*.

Cultivar	Lesions per Leaf		Senescence Rating[z]		NO_3-N conc. $mg \cdot kg^{-1}$	Final 2-leaf Analysis (6 weeks AI)[y]	
	4 weeks AI	6 weeks AI	Prior to Inocu-lation	6 weeks AI	Prior to Inocu-lation	NO_3-N conc. $mg \cdot kg^{-1}$	Lesions per Leaf
Idaho	0.52 b[x]	0.88 a	2.92 a	2.92 a	1426 a	147 a	7.50 a
Fontana	0.22 a	0.77 a	3.42 a	3.08 a	1492 a	385 b	2.08 a
Idaho	0.33 a[s]	0.98 a	1.58 a	2.42 a	3408 a	1262 a	11.75 a
Fontana	0.77 a	1.96 a	2.58 b	2.83 a	3417 a	1706 a	20.42 a

[z] Scale: 0 = leaf dark green, 2 = leaf light green, 4 = mild chlorosis, 6 = major chlorosis.
[y] 2 leaves collected at 6 weeks after inoculation (AI) and assessed for both nitrate-N content and Cercospora leaf blight lesions per leaf.
[x] Numbers in a column within the same section followed by the same letter are not significantly different at P=0.05, Fisher's Protected LSD Test.

Appendix 6: Comparisons Between Leaf Element Concentrations and the Severity of Alternaria and Cercospora Leaf Blight

Materials and Methods

Tissue samples were collected at harvest, processed as described in Chapter 4, and sent to A&L Laboratories East, Inc. (London, Ontario) for a full leaf nutrient analysis. Leaf total N concentrations were compared with the concentration of the other elements in the leaf using linear correlation analysis. Leaf total N concentrations were compared with Alternaria leaf blight (ALB) and Cercospora leaf blight (CLB) area under the disease progress curve (AUDPC), which was determined as described in Chapter 3, using linear correlation analysis. Data were analysed using the PROC Corr procedure of SAS version 8.0 (SAS Institute, Cary NC). A type I error rate of 0.05 was set for all statistical tests.

Results

Leaf total N concentrations were correlated with all of the elements tested in at least one case (Table A4.1). The strongest correlations were between total N and Mg, S, Fe, and Mn concentrations (Table A4.1). Alternaria AUDPC values were correlated with total N, Mg, S, Na, Fe, Al, Mn, and B concentrations in the leaf in at least one case (Table A4.2). Cercospora AUDPC values were correlated with total N, P, Ca, Mg, S, Na, Fe, Al, and Mn concentrations in the leaf in at least one case (Table A4.3). Leaf Na and Mg concentrations had a stronger correlation with both ALB and CLB severity than total N concentration in most cases. Leaf nitrate-N concentrations were not correlated with

ALB or CLB severity because NO_3-N concentrations were very low at harvest, and accurate results could not be obtained using the methods available at A&L Laboratories East, Inc.

Discussion and Conclusions

Since N supply was the only factor altered in these experiments, it is likely that applied N affects the concentration of all of the other nutrients in the leaf. Consequently, the effects of N application rate on carrot yield and disease severity could be caused by any one of the nutrients tested in this study. It is also possible that differences in leaf blight severity altered the concentrations of some of the elements tested. Since Na and Mg were better correlated with disease severity than total N concentration, it is possible that the effect of N application rate on disease severity can be attributed to changes in Na and Mg concentrations in the leaf. It is also possible that ALB and CLB affect the concentrations of Na and Mg in the leaf. Nitrogen also could have caused a dilution effect, by increasing DM production, which could have resulted in a reduction in concentration of the elements in the leaf. Additional research on the interrelationships among the elements tested and disease severity is warranted.

Table A6.1. Linear correlation statistics for the comparison between top and root total N concentrations with concentrations of various macro- and micro-nutrients, aluminum, and sodium in those tissues for carrots grown on mineral and organic soil.

Cultivar	Part	Stat-istic	Linear Correlations With Tissue Total N Concentration											
			P	K	Ca	Mg	S	Na	Fe	Al	Mn	B	Cu	Zn
Mineral Soil														
Idaho	Top	P	0.4709	**0.0186**	0.6609	**0.0019**	0.0869	0.1885	**<.0001**	**<.0001**	**<.0001**	**0.0076**	0.1553	0.5483
		r	0.18	**0.55**	0.11	**0.68**	0.41	0.32	**-0.81**	**-0.83**	**-0.79**	**0.61**	0.35	-0.15
Fontana	Top	P	0.2419	0.1919	0.9382	**0.0003**	0.2778	0.0587	**0.0283**	**0.0420**	**0.0369**	0.1282	0.1488	0.9803
		r	0.29	0.32	-0.02	**0.76**	0.27	0.45	**-0.52**	**-0.48**	**-0.49**	0.37	0.35	-0.01
Idaho	Root	P	0.0994	0.5690	0.1189	**0.0036**	**<.0001**	0.1033	0.3358	0.5338	0.8559	0.3202	0.5747	**0.0298**
		r	0.40	0.14	0.38	**0.65**	**0.88**	0.40	0.24	-0.16	0.05	0.25	0.14	**0.51**
Fontana	Root	P	0.1332	**0.0035**	**0.0003**	**<.0001**	**<.0001**	0.1416	**0.0012**	**0.0084**	**0.0184**	**0.0112**	0.4429	0.3385
		r	0.37	**0.65**	**0.76**	**0.82**	**0.92**	0.36	**0.70**	**0.60**	**0.55**	**0.58**	0.19	0.24
Organic Soil														
Idaho	Top	P	0.1979	**0.0089**	0.2371	0.2894	**0.0152**	0.3384	**0.0167**	**0.0216**	**0.0180**	0.4663	**0.0318**	**0.0013**
		r	0.32	**-0.60**	0.29	0.26	**0.56**	0.24	**0.56**	**0.54**	**0.55**	-0.18	**0.51**	**0.70**
Fontana	Top	P	0.7211	0.4330	0.6791	0.6484	0.2580	0.0542	0.2945	0.4483	0.6565	0.1531	0.6117	0.9295
		r	-0.09	-0.20	-0.11	-0.12	0.28	0.46	0.26	0.19	0.11	-0.35	0.13	0.02
Idaho	Root	P	**<.0001**	0.0634	**<.0001**	**<.0001**	**<.0001**	**0.0133**	0.0698	**<.0001**	**<.0001**	**<.0001**	0.0517	**<.0001**
		r	**0.84**	0.45	**0.83**	**0.80**	**0.86**	**0.57**	0.44	**-0.81**	**0.86**	**0.86**	0.47	**0.86**
Fontana	Root	P	**0.0006**	**0.0011**	**<.0001**	**0.0005**	**0.0006**	0.6828	0.4738	**0.0004**	**<.0001**	**<.0001**	0.2777	**<.0001**
		r	**0.73**	**0.70**	**0.84**	**0.73**	**0.73**	0.10	0.18	**-0.74**	**0.87**	**0.85**	0.27	**0.79**
Soils Combined														
Both	Root	P	**<.0001**	0.0728	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.6019	**<.0001**	**0.0002**	**<.0001**	**0.0012**	**<.0001**
		r	**0.74**	0.21	**0.58**	**0.66**	**0.76**	**0.57**	-0.06	**-0.52**	**0.42**	**0.70**	**0.37**	**0.76**
Both	Top	P	**<.0001**	0.5979	0.9581	**<.0001**	0.1098	**<.0001**	**<.0001**	**<.0001**	**0.0077**	**<.0001**	**<.0001**	**<.0001**
		r	**0.50**	-0.06	-0.01	**0.63**	0.19	**0.57**	**-0.70**	**-0.72**	**0.31**	**0.45**	**0.63**	**0.61**

Table A6.2. Linear correlation statistics for the comparison between Alternaria leaf blight area under the disease progress curve (AUDPC) to carrot leaf tissue nutrient concentrations at harvest.

Cultivar	Stat-istic	Linear Correlations With Alternaria AUDPC													
		N	NO_3^-	P	K	Ca	Mg	S	Na	Fe	Al	Mn	B	Cu	Zn
Mineral-2003															
Idaho	P	**0.0180**	0.2473	0.2135	0.3245	0.2493	**<.0001**	**0.0341**	**0.0034**	**0.0181**	**0.0084**	0.0559	0.2214	0.5888	0.9412
	r	**-0.76**	-0.43	-0.46	-0.37	-0.43	**-0.97**	**-0.70**	**-0.85**	**0.76**	**0.81**	0.65	-0.45	-0.21	0.03
Font.	P	0.1643	0.4978	0.3113	0.8608	0.4341	**0.0059**	0.0541	**0.0023**	0.3043	0.4804	0.3878	0.9349	0.5331	0.9817
	r	-0.51	-0.26	-0.38	0.07	-0.30	**-0.83**	-0.66	**-0.87**	-0.39	-0.27	-0.33	0.03	-0.24	0.01
Mineral-2004															
Idaho	P	0.4922	0.8949	0.7872	0.7797	0.1247	**0.0020**	0.2982	0.1730	**0.0189**	**0.0154**	**0.0191**	0.1442	0.4769	0.8896
	r	-0.26	0.05	-0.11	0.11	-0.55	**-0.88**	-0.39	-0.50	**0.75**	**0.77**	**0.75**	0.53	-0.27	-0.05
Font.	P	0.1061	0.4597	0.6644	0.7737	0.0620	0.7405	0.3307	0.5514	0.5189	0.6329	0.9021	0.3332	0.1830	0.5731
	r	-0.57	-0.28	0.17	0.11	0.64	-0.13	0.37	-0.23	-0.25	-0.19	0.05	0.37	-0.49	0.22
Organic-2003															
Idaho	P	0.9098	0.0792	0.4774	0.5462	0.3240	0.7742	0.5819	**0.0332**	0.9070	0.7035	0.8134	0.6740	0.9200	0.5795
	r	-0.04	-0.61	0.27	-0.23	0.37	0.11	0.21	**-0.71**	0.05	-0.15	0.09	0.16	0.04	0.21
Font.	P	0.1270	0.9842	0.3866	0.5683	0.6839	0.8975	0.9757	0.1523	0.4175	0.6112	0.3364	**0.0234**	0.6968	0.1035
	r	-0.55	-0.01	0.33	-0.22	0.16	0.05	-0.01	-0.52	-0.31	0.20	-0.36	**0.73**	-0.15	-0.58
Organic-2004															
Idaho	P	0.1189	0.3722	0.0674	0.4767	0.6724	0.2346	0.9482	0.1540	0.6880	0.6774	0.8001	0.9868	0.9102	0.5094
	r	-0.56	-0.34	0.63	0.27	0.16	-0.44	0.03	-0.52	-0.16	-0.16	-0.10	-0.01	-0.04	-0.25
Font.	P	**0.0100**	0.5394	0.4053	0.5566	0.0538	0.7280	0.3928	0.3503	0.8892	0.7066	0.7827	**0.0215**	0.4520	0.8102
	r	**-0.80**	0.24	0.32	0.23	0.66	0.14	0.33	-0.35	-0.05	-0.15	0.11	**0.74**	0.29	-0.09
Mineral															
Both-2003	P	**0.0135**	0.2238	0.1915	0.6332	0.1924	**<.0001**	**0.008**	**0.0002**	0.537	0.3501	0.4502	0.5266	0.4019	0.9427
	r	**-0.57**	-0.30	-0.32	-0.12	-0.32	**-0.81**	**-0.61**	**-0.77**	0.16	0.23	0.19	-0.16	-0.21	0.02
Both-2004	P	0.0728	0.5786	0.8601	0.6743	0.8204	**0.0187**	0.6423	0.1163	0.5030	0.3393	0.1342	0.0578	0.1132	0.6909
	r	-0.43	-0.14	0.04	-0.12	-0.06	**-0.55**	-0.12	-0.38	0.17	0.24	0.37	0.46	-0.39	0.10
Organic															
Both-2003	P	0.1380	0.0679	0.4864	0.9372	0.4109	0.8916	0.4132	**0.0010**	0.5641	0.9108	0.8935	0.1249	0.9419	0.5883
	r	-0.36	-0.44	0.18	0.02	0.21	0.03	-0.21	**-0.71**	-0.15	-0.03	-0.03	0.38	-0.02	0.14
Both-2004	P	0.8804	0.4547	0.4081	0.2981	0.1779	0.1365	0.3858	**0.0379**	0.5176	0.4857	0.5887	0.5200	0.8941	0.7133
	r	0.10	0.19	0.21	0.26	-0.33	-0.36	-0.22	**-0.49**	-0.16	-0.18	-0.14	0.16	-0.03	-0.09

Table A6.3. Linear correlation statistics for the comparison between Cercospora leaf blight area under the disease progress curve (AUDPC) to carrot leaf tissue nutrient concentrations at harvest.

Cult-ivar	Stat-istic	Linear Correlations With Cercospora AUDPC													
		N	NO_3^-	P	K	Ca	Mg	S	Na	Fe	Al	Mn	B	Cu	Zn
Mineral-2003															
Idaho	P	**0.0262**	0.2805	0.5793	0.3979	0.8332	**0.0028**	0.0570	**0.0002**	**0.0305**	**0.0122**	**0.0125**	0.4353	0.7516	0.6384
	r	**-0.73**	-0.40	-0.21	-0.32	-0.08	**-0.86**	-0.65	**-0.94**	**0.71**	**0.79**	**0.78**	-0.30	-0.12	0.18
Font.	P	0.0977	0.2758	0.2637	0.9757	0.6089	**0.0195**	0.0735	**0.0149**	0.4390	0.4757	0.6564	0.8004	0.5079	0.9210
	r	-0.59	-0.41	-0.42	0.01	-0.20	**-0.75**	-0.62	**-0.77**	-0.30	-0.27	-0.17	0.10	-0.25	-0.04
Mineral-2004															
Idaho	P	0.7990	0.6277	0.4999	0.4477	**0.0343**	**0.0101**	0.1747	0.0842	0.1435	0.1056	0.2687	0.2038	0.9094	0.9139
	r	0.10	0.19	-0.26	0.29	**-0.70**	**-0.80**	-0.50	-0.61	0.53	0.57	0.41	-0.47	0.04	-0.04
Font.	P	**0.0416**	0.5188	0.9229	0.5210	0.2962	0.3564	0.6158	0.1772	0.8493	0.9721	0.6426	0.5301	0.3270	0.8831
	r	**-0.69**	-0.25	-0.04	0.25	0.39	-0.35	0.19	-0.49	-0.07	0.01	0.18	0.24	-0.37	0.06
Organic-2003															
Idaho	P	0.6126	0.3389	0.7575	0.6510	0.7642	0.5694	0.8648	0.2792	0.9844	0.6959	0.8305	0.9915	0.9403	0.3365
	r	-0.20	-0.36	0.12	0.18	0.12	-0.22	0.07	-0.41	-0.01	-0.15	0.08	0.00	0.03	0.36
Font.	P	0.8328	0.1006	0.9084	0.7982	0.6309	0.7882	0.6334	0.8148	0.6189	0.2325	0.8932	0.4573	0.6406	0.7055
	r	0.08	0.58	0.05	-0.10	0.19	0.10	0.19	0.09	0.19	0.44	0.05	0.29	0.18	-0.15
Organic-2004															
Idaho	P	0.1752	0.2835	**0.0381**	0.5937	0.7291	0.3268	0.8051	0.2357	0.5860	0.5900	0.6838	0.8384	0.7886	0.5533
	r	-0.50	-0.40	**0.69**	0.21	0.14	-0.37	0.10	-0.44	-0.21	-0.21	-0.16	-0.08	-0.10	-0.23
Font.	P	**0.0118**	0.5853	0.2772	0.2250	0.0827	0.6542	0.2993	0.4056	0.5741	0.4314	0.8084	0.0695	0.9878	0.7011
	r	**-0.79**	0.21	0.41	0.45	0.61	0.17	0.39	-0.32	-0.22	-0.30	-0.09	0.63	0.01	-0.15
Mineral															
Both-2003	P	**0.0181**	0.2746	0.0877	0.3096	0.3672	**0.0001**	**0.0356**	**0.0002**	0.2003	0.1191	0.0704	0.5823	0.5571	0.7853
	r	**-0.55**	-0.27	-0.41	-0.25	-0.23	**-0.78**	**-0.50**	**-0.77**	0.32	0.38	0.44	-0.14	-0.15	-0.07
Both 2004	P	0.1089	0.8580	0.7123	0.1366	0.2518	**0.0160**	0.3437	**0.0238**	0.6355	0.4271	0.3286	0.2165	0.4367	0.6814
	r	-0.39	-0.05	-0.09	0.36	-0.28	**-0.58**	-0.24	**-0.53**	0.12	0.20	0.24	0.31	-0.20	0.10
Organic															
Both-2003	P	0.6225	0.2778	0.9798	0.3449	0.7328	0.6694	0.3409	**0.0190**	0.7966	0.9728	0.7640	0.6061	0.8153	0.0956
	r	-0.12	-0.27	0.01	0.24	0.09	-0.11	-0.24	**-0.55**	-0.07	0.01	0.08	0.13	0.06	0.40
Both-2004	P	0.4952	0.5582	0.3542	0.2860	0.1201	0.1376	0.4056	0.0576	0.4021	0.3939	0.4334	0.8065	0.6411	0.7201
	r	0.17	0.15	0.23	0.27	-0.38	-0.36	-0.21	-0.46	-0.21	-0.21	-0.20	0.06	-0.12	-0.09