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Managing Nitrogen For Quality Carrot
Tops Using Remote Sensing

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MANAGING NITROGEN FOR QUALITY CARROT TOPS USING REMOTE SENSING

By

Jeanette Leah Makries

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Abstract

MANAGING NITROGEN FOR QUALITY CARROT TOPS USING REMOTE SENSING

By

Jeanette Leah Makries

Michigan carrots are mechanically harvested; therefore quality tops are essential for a successful harvest. During the process of harvesting, the tops are grabbed by mechanical arms that lift the loosened carrots and carry them up a conveyor. Site specific management using remote sensing may be useful in maintaining healthy tops without over fertilizing the roots. A two year study was conducted at the Montcalm Experiment Station and Sandyland Farms; Montcalm County. Four replications of four N treatments, 45, 90, 135, and 180 kg ha^{-1}, were arranged in a randomized complete block design at all locations. N content of soil, petioles, and harvested plants was compared to individual reflectance using narrow wavebands centered at 460, 510, 560, 610, 660, 710, 760, and 810 nm and selected vegetation indices, NDVI, SAVI, TSAVI, and GNDVI.

Visible wavebands centered at 560, 610, and 710 were the earliest and most consistent to correlate with treatments, petiole-N, and selected harvest measurements where r^2 was as high as 0.90. NIR reflectance at 760 and 810 nm was weakly correlated with plant N status where canopy coverage was affected by variables other than N treatments and when the canopy reached full coverage affecting the sensitivity of indices to N status. GNDVI out performed the other indices; soil adjustment did not enhance the usefulness of the indices.

This Thesis is
Dedicated
To my husband Jim
Who patiently supported my endeavors, and shared
Many hours with this project, and

To my sons Jeffery and AJ
Who have also shared many hours with my studies
And who have taught me as much about courage and
Determination as I have taught them

And to my parents
Ernie and Eleanor, who taught me to will, to help myself,
And persevere, and who have been ever
Vigilant in their watch over me

And to my brothers and sisters
Whose continuous encouragement
Helped me through
This process

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Introduction

Managing Nitrogen for Quality Carrot Tops Using Remote Sensing

Agricultural studies involving remote sensing are driven by the need for precision agriculture for the purpose of improving crop performance and environmental quality (Pierce and Nowak, 1999; Kutcher et al., 2005). As defined by Pierce and Nowak (1999), precision agriculture is the application of technology and principles to manage spatial and temporal variability associated with all aspects of agricultural production. Soil and crops are managed by soilscapes, management zones, and the management of non-crop periods (Pierce and Nowak, 1999; Lauzon et al., 2005; Allmaras et al., 1998). The fact that the soil supply of nutrients and plant demand, and nutrient loss through leaching, erosion, and runoff vary in space and time indicates there are significant opportunities for precision management of soil fertility (Pierce and Nowak, 1999).

Precision agriculture must fit the needs and capabilities of the farmer (Pierce and Nowak, 1999). It will only be economically beneficial if questions pertaining to type of variability present and potential management opportunities are addressed (O'Halloran, 2005), because the benefit is not derived from the technology itself, but from the management decisions resulting from its use (Pierce and Nowak, 1999). Precision management of crop production must be an improvement over whole field management (Pierce and Nowak, 1999). If the parameter of interest is homogenous or random, then the cost does not warrant its use; but as the degree of spatial and temporal dependence increases so do the prospects for precision management (Pierce and Nowak, 1999). It is necessary to report simultaneously on both spatial and temporal variables. Some spatial patterns develop over time and the cause and effect may exist in time but not in space; even though the degree of difficulty in achieving precision management increases with temporal variance (Pierce and Nowak, 1999).

Soil productivity and spatial variability in crop growth and yield have always been realities of farming (Pierce et al., 1995), and vary across fields as the result of the interaction of topography, soil properties, and management practices (Kravchenko et al., 2005). Water distribution is also a function of this dynamic trio, and along with weather conditions, varies from year to year (Kravchenko et al., 2005). Therefore, crop susceptibility to erosion, and surface and groundwater vulnerability to pollution exist in specific spatial patterns (Nowak and Korsching, 1998; Allmaras et al., 1998). Assessment of variability is the first step in precision management (Pierce and Nowak, 1999). Lauzon et al. (2005) found soil test results reasonably correlated with topographic-position variables from site to site. Pierce et al. (1995) found on the average, each of three fields in southern Michigan showed optimum pH and medium to high soil test results. Soil fertility, however, generally ranged from deficient to excessive for most parameters measured. More specifically, Kutcher et al. (2005) cited several studies that found crop productivity varying between slope position as a result of differing conditions particularly moisture and fertility. The soil physical properties or landscape undulation may be more important than fertility in explaining yield variation; particularly in their effect on water availability (Pierce et al., 1995). Soil moisture, as it changes across an undulating landscape, affects the potential for N mineralization, immobilization, denitrification, and leaching (Kutcher et al., 2005). There are many researchers whose studies are dedicated to the identification of controllable variability, and determination of the intensity of measurement at which profitable precision can be achieved. Among them are authors featured in the following chapters including Schepers et al. (1992, 1996), Blackmer et al. (1994, 1996a, 1996b), and Osborne et al. (2002).

Site-specific management may improve economic returns and reduce environmental contamination (O'Halloran, 2005), because it involves the variable management of soils, crops, and pests according to conditions within a field (Pierce et al., 1995). It provides farmers the potential to apply the exact requirement of nutrients at each given location (Lauzon et al., 2005; Larson et al., 1998). In the previously cited study in southern Michigan, the cost of over fertilizing a corn crop when fertilizer was applied uniformly was only a few dollars per hectare; however, the estimated yield loss from under fertilization could be greater than 2 Mg ha^{-1} (Pierce et al., 1995). Profitable site-specific management includes the ability to accurately locate one's self in the field; vary input; have a reasonable understanding of how the nutrient or crop response will vary across the field; and, the level of variability must be enough to make the investment worthwhile and it must be manageable (O'Halloran, 2005).

Geostatistics has been adapted for use in site-specific management to assess spatial variability. Spatial estimations are made using points and interpolation, but one must decide on the appropriate scale (Pierce and Nowak, 1999; Lauzon et al., 2005). The sample point unit, design, and map accuracy should result in a quality that has value for management decisions and be appropriate for available equipment (Pierce and Nowak, 1999). Sampling intensity should be driven by field characteristics rather than cost, and the distance between samples should be sufficiently small so that resulting data points are spatially related (Pierce and Nowak, 1999, Lauzon et al., 2005). Researchers at

Oklahoma State University found that the field element size is seldom larger than 1 m^2 (Dept. of Plant and Soil Sciences Oklahoma State University, 2004); however, even if sampling intensity is reduced to a 30 m grid, there is economic concern (Lauzon et al., 2005).

Precision agriculture includes five general groups of technology: computers, GPS, GIS, sensors, and variable rate control (Pierce and Nowak, 1999). Sensors may provide the cost effective solution by which sampling intensity can be driven by field characteristics. They have a fixed initial cost that actually decreases as sampling intensifies (Pierce and Nowak, 1999). This means that, the sampling scheme can be determined by the sensors capability and the nature of sampled parameters independent of cost or difficulty, in contrast to traditional sampling (Pierce and Nowak, 1999). Remote sensing of a growing crop will reveal stresses that impact the crop during the growing season, and intervention strategies can be applied to meet the demand during the rapid uptake phase of growth (Pierce and Nowak, 1999). It is even more applicable where the temporal component of spatial variability is medium to high as with N management versus P, K and pH where temporal variability is low (Pierce and Nowak, 1999).

This study was focused on the use of sensors, specifically above canopy proximal sensing of the spectral reflectance, one form of remote sensing. According to Bronson et al. (2005), estimation of crop N using proximal sensing has gained strong interest. Height above the soil varies from study to study and examples range from directly over the row (Dept. of Plant and Soil Sciences Oklahoma State University, 2004), to several meters high (Bronson et al., 2005; Ma et al., 2001; Osborne et al., 2002). Remote sensing holds real promise for precision agriculture because of its potential for monitoring spatial variability over time at high resolution (Pierce and Nowak, 1999). Using sensing to discover deficiencies may be better adapted to precision management than those that rely on soil sampling (Pierce and Nowak, 1999), or may supplement preplant soil test data (Bronson et al., 2005).

The amount of electromagnetic energy reflected or emitted from an object varies by wavelength as determined by the object's physical and chemical structure (Pierce and Nowak, 1999). One sampling can measure many plants and monitor many conditions (Blackmer et al., 1996). A single measurement can be used to construct different images of a target using a single waveband or a combination of wavebands depending on the parameter of interest (Pierce and Nowak, 1999). For example, spectra at 550 to 560 nm and at 660 nm are associated with plant chlorophyll content. Wavebands at approximately 900 nm are absorbed by iron oxide and may be associated with soil characteristics (Fontes and Carvalho, Jr., 2005). Wavebands at 960, 1200, 1420, 1920, and 2620 nm are water absorption bands (Lillesand and Kiefer, 2000; D.P. Lusch, personal communication, 2001). An image developed from these bands may reveal the water content of the canopy in the field, and over time track the temporal trend of seasonal moisture distribution. Plant litter can be discriminated from soil using wavebands at 1730, 2100, and 2300 nm which are primarily associated with N, cellulose, and lignin, respectively (Daughtry et al., 2005). Plant residue lacks the spectral response of green vegetation, but still retains alcoholic-OH groups such as sugar, starch and cellulose which are absent in soils. Although researchers have studied the relationship of spectral measurements to plant physiological and biochemical aspects for some time now, new and more complex indices are under design using more precise hyperspectral radiometers. Such physiological and biochemical aspects include chlorophyll, carotenoids, and water content, as well as cellulose, lignin and dry matter (Zarco-Tejada et al., 2005).

One approach to precision N management is to develop site-specific intervention strategies based on crop monitoring of N status using remote sensing (Pierce and Nowak, 1999). There are many representative studies exemplifying this approach. Some of those studies are summarized in the next chapters. The first step is to monitor N concentration by measuring plant or canopy reflectance of light. The second step is to estimate N fertilizer requirements using a relationship established between reflectance and N content (a reference strip may be used as a standard). The final step is to fertilize the crop to optimum N content (Pierce and Nowak, 1999).

To date, the bulk of agricultural research using remote sensing has concentrated on agronomic crops. Since they are mechanized and precision agriculture really gained momentum with the development of the yield monitor (Pierce and Nowak, 1999), it follows that subsequent advances in agricultural remote sensing should gain popularity first with mechanized crops. The field size of agronomic crops is generally large enough to necessitate the ability to sample on a large scale. However, there are many vegetable crops that may also benefit from remote sensing and precision agricultural management, especially those that are mechanized such as carrot.

The following chapters present the results of a two year study in the N management of carrot tops using remote sensing. Quality tops, even though they are not the income producing part of the plant, are essential for a successful carrot harvest.

Michigan carrots are mechanically harvested. During the process of harvesting, the tops are grabbed by mechanical arms that uproot the loosened carrots and carry them up a conveyor. Weak tops will break off and leave the carrots in the ground resulting in lost yield. Site specific management using remote sensing to monitor nutrient status may provide the means to maintain healthy tops without over fertilizing the roots.

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Chapter I

Effect of Nitrogen Applications on Soil NO_3^-, Plant Nitrogen Status, and Biomass Production in Carrot

Introduction

Carrot (*Daucus carota L.*) is harvested for market every month of the year in the United States (McGiffin et al., 1997; Mills, 2001). Worldwide, carrot is a minor crop; 18.5 million tons of carrots were produced in 1998 on 794,000 ha (Suojala, 2000). The National Agricultural Statistics Service (USDA NASS, 2002) reported that in 2001, the United States produced 31.3 million cwt (1.4 million Mg) of carrot on over 100,000 acres (41,000 ha) worth $545 million out of more than $10 billion in principal commercial vegetable production. The carrot share of the United States market was just over 5% (USDA NASS, 2002). California is the leading US producer of carrot where it is grown year-round. Other states that are ranking producers are Texas, Georgia, Washington, Michigan, and Wisconsin.

In 2001, Michigan ranked third in the US for fresh market production and fifth for processing carrot (USDA NASS, 2002). Michigan carrot production is concentrated in five counties: Muskegon, Newaygo, and Oceana growers produce carrots predominantly for processing, of which one-third is used in baby food (Carrot Ramp, 2003); fresh market carrot production is concentrated in Montcalm and Lapeer counties.

In addition to its commercial value, carrot provides an economical source for seven to eight times the recommended daily allowance of vitamin C. It is also high in fiber, potassium and vitamins A, B, D, and E. Carrot contains calcium, is rich in mineral salts, high in beta-carotene, and contains smaller amounts of essential oils, carbohydrates, and nitrogenous compounds. Carrot is well known for its sweetening, antianaemic, healing, diuretic, remineralizing, and sedative properties (MDA, 2002).

Finally, carrot may help control excess soil NO_3^-. The deep fibrous root system can effectively lower excessive accumulations that have leached deeper into the soil profile (Warncke, 1996; White and Strandberg, 1978).

The objective of this study was to evaluate the field response of carrot to nitrogen treatments at four locations over a two-year period (2001, 2002).

Literature Review

Carrot (*Daucus carota L.)*, shares the same family (*Apiaceae)* as celery, fennel, parsnip, and parsley. It emerges from seed with two strap-like cotyledons followed by rosettes of doubly compounded leaves rising from the crown. A taproot develops from the hypocotyl (Mills, 2001), and the hypocotyl will eventually form about 2.54 cm of the upper part of the storage root (Suojala, 2000). During the first 24 days after emergence, early and rapid growth of the taproot in the temperature range of 16-24°C is striking, with little secondary or tertiary root development and no visible secondary thickening (White and Strandberg, 1978). Secondary thickening begins with initiation of the secondary cambium. This enlarging causes cells of the cortex and endodermis to rupture, at which point the orange color appears (Suojala, 2000). The size of individual roots increases with maturity and is affected by plant population, which is a function of the crop end use. For production purposes, root uniformity is a common demand of processors (Suojala, 2000). Although early top growth is slower than root growth, the tops generally produce greater biomass (White and Strandberg, 1978). The length of the growing season varies with end use and available markets, variety, geographical location, and time of planting (Hipp, 1978). Michigan carrots are harvested 80 to 180 days after planting (USDA, 1999, Zandstra et al., 1986).

Carrot is a cool season crop that demands specific growing conditions for successful commercial production and effective use of N applications. The crop is grown best at 60 to 70° F (16 to 21°C) (Golz and Aakre, 1993; Mills, 2001; Fritz et al., 1998; MDA, 2000; Zandstra et al., 1986). While young seedlings can withstand mild frost, high temperatures can result in damage (USDA, 1999). High temperatures cause greater respiration in the leaves reducing color development and sugar accumulation as the root matures, which results in a strong unpleasant flavor (Mills, 2001; Zandstra et al., 1986). Alaska, with its cool climate, boasts of a high quality carrot due to greater sugar accumulation in the roots (Epps, 1970). It is this cool season requirement that allows Florida to use carrot as a winter crop (Hochmuth et al., 1999; McCollum et al., 1986) and Midwestern states such as Michigan to plant in early spring (USDA, 1999). California, with its varied climate zones, high desert, southern desert, central coast, and central valleys, grows carrot continuously (McGiffin et al., 1997).

For optimal carrot production, the soil should be warm, loose, deep, and well drained (Epps, 1977; MDA, 2002; Zandstra et al., 1986). It is generally agreed that carrot grows best on coarse mineral or organic soils (Fritz et al., 1998; Hanlon et al., 2002; Mills, 2001; Hochmuth, 1999; Epps, 1970; Golz and Dwight, 1993; McGiffin et al., 1997). Heavy soils are less desirable even if uniform moisture is maintained, because carrot is very sensitive to soil compaction (Golz, 1993). Compact, cold, and poorly drained soil causes crooked forked roots (Epps, 1970; MDA, 2002; USDA, 1999). The ideal mineral soil is silt loam, according to McGiffin et al. (1997), because it has the best combination of water holding capacity and drainage. Other soil recommendations range from loamy sand to sandy loam (Epps, 1970; Hipp, 1978; Hochmuth, 1999; MDA, 2002; Sanderson, 1997; Warncke 1996). In Michigan, carrot is primarily grown in deep, well-drained muck with a pH range of 5.5 to 5.8, and in mineral soils with a pH range of 6.2 to 6.8 (USDA, 1999; Zandstra et al.,1986).

Carrot is directly seeded into the soil; transplanting disturbs the taproot and prohibits proper hypocotyl development. Seeding population varies depending on the purpose for which it is grown, and the planting density is selected to provide the greatest number of carrots of the size required for the specific market (McCollum et al., 1986). Varieties used in production of "baby carrots" are planted at the highest population, 80 to 100 seeds per bed foot [with 20 to 40 in. (51 to 102 cm) wide beds] (Fritz et al., 1998). Fresh market varieties are planted 20 to 30 seeds per row foot and processing varieties are generally planted 10 to 20 seeds per row foot (Mills, 2001; Fritz et al., 1998, Golz and Aakre, 1993). Carrot may be sown in beds or nonbedded. Total yield, root size, and uniformity at harvest are a function of stand establishment (Finch and Savage, 1987). In Michigan, growers commonly interseed barley or other small grains with carrot to protect emerging plants from wind damage (Zandstra and Warncke, 1993).

A uniform water supply, as well as good soil fertility, is critical for the development of good color and formation of uniform root size (McGiffin et al., 1997; Mills, 2001). The University of Alaska (Epps, 1997), the University of California (Fritz et al., 1998), and Michigan State University recommend 2.5 to 3.8 cm of water per week, with seasonal totals of 25.4 to 35.6 cm in Michigan (Zandstra et al., 1986) and 35.6 to 38.1 cm in California (Fritz et al., 1998). The soil should be soaked completely to avoid separation between sub-soil and surface-soil moisture that may cause differential growth and cracking (Zandstra et al., 1986). Irregular watering, such as significant wet/dry patterns, may result in root splitting (McGiffin et al., 1997), or rough, lumpy carrots with obvious growth rings (Fritz et al., 1998). Carrots are most sensitive to moisture stress during seed germination and root enlargement promoting small, woody and poorly flavored roots with growth cracks (Fritz et al., 1998). Excessive water discourages good color and encourages soil borne diseases (Kelly, 1998; McGiffin et al., 1997).

Carrot is especially susceptible to weed competition because emergence and early top growth is slow (White and Strandberg, 1978; MSU and MDA, 2000). Since mechanical cultivation may injure roots, chemical herbicides are recommended (Epps, 1977; MSU and MDA, 2000). Linuron has been shown to be most effective (Epps, 1997; Bell, 2000), and preplant applications may prove particularly successful in controlling weeds (Kelly, 1998). Alternaria (*Alternaria dauci)* and Cercospora (*Cercospora carotae)*, both foliar blights, can cause serious damage to top quality. In some areas, including Michigan, where carrot is harvested using the tops to lift the plant out of the soil, weakened tops result in yield reduction. Pressure from these diseases cause fungicides to be the primary pesticide applied to carrot.

Nitrogen (N) is a component of chlorophyll, all proteins and many other compounds in plants, and is an essential nutrient for plant health (Carrot Ramp, 2003; Marshner, 1998). It is the most limiting nutrient for crop production because of the large need for it by plants and the limited ability of soils to supply available N. Only about 1%

or less of the total N in soils is available to plants and microorganisms as NO_3^- or exchangeable NH_4^+, which is rapidly consumed or susceptible to leaching. It must be replaced by fertilizer applications or by mineralization (Foth and Ellis, 1997). The following studies describe past experiences with carrot response to various N limiting situations due to reduced applications and excessive rains.

Sanderson (1997) conducted a five-year study on Prince Edward Island, on soils of loamy sand to sandy loam texture [Orthic Humo-Ferric Podzols (Orthic Podzol in FAO system)], to determine whether a reduction in N rate had any effect on carrot yield. During a three year period at six locations, N applications were reduced by as much as 40% from 72 to 44 lb A^{-1} (80.6 to 49 kg ha^{-1}) with no effect on yield. During an additional two-year study, at four locations, 132 lb A^{-1} (148 kg ha^{-1}) applications were reduced by 67% when the 88 lb A^{-1} (98.6 kg ha^{-1}) preplant application was eliminated. No reduction of yield was observed, and the root weight, diameter, and length were not affected by the reduction in N. There were no differences between any of the 10 locations based on preplant or split applications. Baseline N levels were not included in the information given.

Hemphill and Jackson (1982) also reported no effect on carrot yield with N treatments ranging from 0 to 240 lb A^{-1} (0 to 269 kg ha^{-1}). Their study on Williamette silt loam (fine-silty, mixed, mesic, Pachic Ultic Argixeroll) focused on pH levels as a limiting factor and reported that generally higher yield was associated with a pH of 5.1 to 5.7. Baseline N levels were not included.

Hipp (1978) conducted a study at the Weslaco Texas Agricultural Experiment Station on soil of sandy loam texture, and related the N requirement of carrot to the length of the growing season. He found that of the four N treatments, 0, 56, 112, and 168 kg ha^{-1}, applied preplant, maximum yield was obtained from the 112 kg ha^{-1}, but not before 128 days or more after planting. Extending the season another 15 to 33 days promoted higher yield and more definitive differences between treatments. Baseline N level was reported at 65 kg ha^{-1} in the 0 to 120 cm profile.

In a study on coarse textured soils [McBride sandy loam (coarse-loamy, mixed, frigid, Oxyaquic Fragiorthods) and Montcalm loamy sand (coarse-loamy, mixed, frigid, Alfic Haplorthods)] where leaching of NO_3^- is a concern, Warncke (1996) reported that where residual N from the previous corn crop, applied manure and preplant N at the rate of 45 kg ha^{-1} totaled as much as 150 kg ha^{-1} by June 25, additional applications did not affect yield, when harvested 135 days after planting. In another study in which residual or baseline N was 44 kg ha^{-1} and significant rainfall leached N into the soil profile beyond the normal 30 cm sampling depth, root and shoots were still significantly affected by treatments (Warncke, 1996). This study also revealed that a single N application of 90 kg ha^{-1} produced root yields and top growth comparable to yields from plots receiving higher and more frequent applications.

A study on early carrot growth showed that carrot is capable of making use of indigenous N that has leached below the normal sampling depth of 30 cm. After just 24 days from emergence the maximum average length of the taproot was 38.5 cm, although a few reached a length of 43 cm (White, 1978). Even though the study was conducted in pots it shows that carrot is capable of reaching N whether it has leached due to rain or over time from the previous season. Warncke (1996) provides field evidence that carrot is capable of accessing N deeper in the profile. A combination of soil and petiole NO_3^-

testing may be the best approach to managing N for carrot (Warncke, 1996).

Reduction in N applications helps prevent leaching and reduces cost to growers; it is also important because carrot is capable of accumulating and storing excessive N in the storage root, though the excess does not contribute to the yield (Warncke, 1996). Excess storage can be a food consumption concern especially in baby food (Warncke, 1996; Carrot Ramp, 2003). In 1989, Evers found that excess N also led to a reduced concentration of sugar in roots (Evers, 1989). Marshner (1998) indicated that as the N supply increases so does the soluble N, especially in leaves and storage organs with high water content. As the level of N increases sucrose, polyfructosan and starch decrease. It is important to consider subsoil sampling for baseline measurements of N, similar to Hipp (1978), since the taproot will reach the subsoil before it is time to sample for sidedressing.

While there is concern about excessive N in the roots, the quality of carrot tops is equally important. In addition to providing photosynthates to the plant, many growers use the tops to lift the roots out of the soil at harvest. For this reason many growers use frequent N applications to keep tops healthy, but timing of the frequent applications is essential. An application too close to harvest may contribute to residual soil nitrate and to increased N content in the roots rather than contributing to healthy tops (Warncke, 1996). Sufficient N also reduces the potential for disease infection. N deficiency in carrot tops can be difficult to detect, often the leaves have a healthy green appearance but the height of tops throughout the field may be irregular (McGiffin et al., 1997). Twenty tons per acre (44.8 Mg ha^{-1}) of carrot removes about 100 lb A^{-1} N (112 kg ha^{-1}) (Zandstra et al., 1986), and Michigan State University's recommendation is based on replacement only at

100 lb A^{-1} (Warncke et al., 1992). Other recommendations range from 60 to 150 lb A^{-1} (67 to 168 kg ha^{-1}), depending on the location and soil type (Walworth, 1998; Golz and Aakre, 1993; Fritz et al., 1998, McGiffin et al., 1997, Mills, 2001). Split applications are recommended to help avoid leaching and runoff (Warncke, 1996). They are recommended as a sidedress four to six weeks after planting to prevent early excessive N-uptake, which promotes excessive vegetation, and delays root development (Mills, 2001, Warncke et al., 1992). In addition, too much preplant N may cause forking (McGiffin et al., 1997).

This chapter presents results of the field response of carrot to N treatments in a study at four locations in Montcalm County, Michigan over a two-year period, where the response to N applications is the focus of this study.

Materials and Methods

Experimental Sites

Field studies were conducted in 2001 and 2002 at four locations in Montcalm County, Michigan with one site split between two varieties in 2002. The soils in this county developed from glacial debris left upon the final retreat of the Wisconsin glacial age approximately 15,000 years ago. Soil differences throughout the county are due to differences in texture, mineralogical composition of the parent material, and drainage. Glacial deposits ranged from 30 to 91m thick; therefore, bedrock did not directly affect the development of the soil. The county at large was originally forested (Soil Survey, Montcalm Co., 1960).

Plots in 2001 and 2002 were located at the Michigan State University Montcalm

Experiment Station, Douglass Township, in the southern ½ of Section 8, T11N, R7W. The experimental plots were located in Range 1 SW in 2001 and in Range 15 SE in 2002. The soil is a well drained to moderately well drained loamy sand to sandy loam, moderately low in organic matter, of the Hillsdale-Spinks map unit (Hillsdale: coarse-loamy, mixed, mesic Typic Hapludalfs; Spinks: sandy, mixed, mesic Psammentic Hapludalfs). This soil was formed on till plains from loamy sand to sandy loam parent material. A 2 to 6% slope declines from north to south at these ranges (Soil Survey, Montcalm County, 1960; D.L. Mokma, personal communication, 2003). The soil surface at the Experiment Station is coarse gravelly to cobbly.

In 2001, the second field site was located along the south side of Deaner Rd, in the NW ¼ of Section 36, T12N, R9W (Winfield Township). This site belongs to Sandyland Farms, and consists of Plainfield Sand, loamy substratum, (mixed, mesic, Typic Udipsamments) formed on old lake plains in sand over glaciofluvial materials. Organic matter content is low and the slope is generally 0 to 2 % (Soil Survey, Montcalm County, 1960; D.L. Mokma, personal communication, 2003).

In 2002, the second field site was located west of Masters Rd. on Sandyland Farms at the mid-point of the eastern ½ of Section 27, T12N, R9W (Winfield Township). The soil is a Plainfield Sand (mixed mesic Typic Udipsamments) sloping 2 to 6% from west to east at this location, and developed from well-drained sand (Soil Survey, Montcalm County, 1960; D.L. Mokma, personal communication, 2003).

Plot Design and Management Protocol

Four replications of each of four N treatments were arranged in a randomized complete block design at all four locations. Plots were situated so as to minimize heterogeneity across the treatments.

At the Experiment Station, carrots were planted in beds, May 8, 2001 on Range 1, and May 7, 2002 on Range 15 in an east to west direction. Each bed consisted of three rows with three lines to a row and each 4.6 x 15.0 m plot contained three beds. Sixteen plots were planted with Diamond Cut (XPH18006, Seminis/Asgrow), a fresh market cultivar, in both seasons. Goliath (PS30489, Petoseed), a processing cultivar, was not replicated in 2001; only four plots, each representing a treatment, were planted to provide another cultivar-specific coloration to contrast with the Diamond Cut. The contrast was intended to address the potential need for a field-specific reference strip. In 2002, 16 plots were also planted with Goliath; that became the fifth site location. Granular urea [$(NH_2)_2CO$, 46-0-0] was broadcast in three applications according to target season totals of 45, 90, 135, and 180 kg N ha^{-1} (Table 1).

The Sandyland fields, in both seasons, were already established when plots were set up in four replications of the four N treatments. Carrots were planted in mid-April on raised beds. Each bed had three rows with three lines in each row. Barley was planted between rows to protect emerging carrots and was killed off with fluazifop-P-butyl once the carrot plants were established. The Deaner Rd. field (2001) was planted in a north to south orientation with a combination of Asgrow B1 (Asgrow) and Prime Cut 59 (Sunseeds) grown for "cut and peel" production. Plots were located between the second and fourth towers of the center pivot irrigation system. N treatments were broadcast in three applications with granular urea (Table 1). The Masters Rd. field (2002) was planted in Sugar Snax 54 (Sunseeds) in an east to west direction. Plots were located between the first and third irrigation towers. Urea was applied in two applications totaling 20, 59, 98 and 136 kg ha $^{-1}$ N (Table 1).

Table 1. N fertilizer (urea) split applications broadcast on the indicated dates, listed by treatment number at the four field locations.

N fertilizer applications kg ha^{-1}									
	2001					2002			
	Experiment Station					Experiment Station			
Trt[†]	6/13	7/11	8/9	Total	Trt	6/18	7/29	8/24	Total
1	45	--	--	45	1	--	22	23	45
2	45	22	23	90	2	34	28	28	90
3	45	45	45	135	3	66	34	35	135
4	45	67	68	180	4	101	39	40	180
	Sandyland (Deaner Rd)					Sandyland (Masters Rd)			
Trt	6/13	7/6	8/1	Total	Trt	7/3	7/29		Total
1	45	--	--	45	1	--	20	--	20
2	45	34	11	90	2	34	25	--	59
3	45	56	34	135	3	66	32	--	98
4	45	78	57	180	4	100	36	--	136

[†]Trt = Treatment

Weeds at the Experiment Station were controlled with linuron (3-(3, 9-dichlorophenyl)-1-methoxy-1 methylurea) and hand weeding. Chlorothalonil (tetrachloroisophthalonitrile) was used to control Alternaria blight (*Alternaria dauci*) and Cercospora leaf spot (*Cercospora carotae*), serious fungal diseases for Michigan carrots that affect top quality (Center for Integrated Pest Management MSU, 1999; Michigan FQPA Residue Report, 2000). Chlorothalonil was supplemented with copper hydroxide in 2002 upon the discovery of Bacterial Blight (*Xanthomonas carotae*) in the Goliath cultivar. Weeds in the Sandyland fields were controlled with linuron and fluazifop-P-butyl. Chlorothalonil was used to control fungal diseases and cyfluthrin (Cyano (4-fluoro-3-phenoxyphenyl) methyl 3-(2, 2-dichloroethyl)-2, 2-dimethylcyclopropanecarboxylate) was applied to control insects.

Rainfall, recorded by the Automated Montcalm Research Farm Weather Station, and irrigation records for the Experiment Station plots are provided in Table 2. During 2001, irrigation was delivered with a "big gun" irrigator, and in 2002, by stationary overhead sprinklers. The Sandyland Farms locations were irrigated with a center-pivot system during both seasons at the rate of 3.0 to 3.8 cm per week delivered in multiple applications.

Agronomic Measurements and Sample Analysis

Baseline soil samples were taken at planting at the Experiment Station and before the first N treatment at the Sandyland locations. Additional in-season soil samples were taken prior to fertilizer applications and at harvest. Eight cores per sample, approximately 30 cm deep, were pulled from alternating sides of the middle row of the middle bed of each plot. Soil samples were dried at 60°C, ground, and analyzed for NO_3^- and NH_4^+ with a 1N KCl extractant.

Carrot petioles were sampled for petiole sap NO_3^- periodically throughout the season. Ten to twenty petioles of the youngest fully extended leaves were chosen from the middle row of the middle bed of each plot. The leaves were discarded in the field and the petioles transported in a cooler. When necessary the petioles were refrigerated prior to NO_3^- determination. A small segment cut from the middle of the petioles was squeezed through a garlic press, and a few drops of the sap were placed on the electrode surface of a Cardy Nitrate Meter (Horiba Group, Japan) to measure the NO_3^- concentration (Warncke, 1996). Subsequently, the remaining tissue was dried at 60°C, ground, and analyzed for total N concentration using the Kjeldahl Method.

Table 2. Rainfall recorded and irrigation amounts delivered at the Montcalm Experiment Station during 2001 and 2002. Irrigation at Sandyland was estimated at 3.0 to 3.8 cm per week

2001				2002			
	---cm---				---cm---		
Week of	Rainfall†	Irrigation	Total	Week of	Rainfall†	Irrigation	Total
Apr 1	3.99	0.00	3.99	Apr 1	0.48	0.00	0.48
Apr 8	0.91	0.00	0.91	Apr 7	1.93	0.00	1.93
Apr 15	1.80	0.00	1.80	Apr 14	1.52	0.00	1.52
Apr 22	1.63	0.00	1.63	Apr 21	2.34	0.00	2.34
Apr 29	0.00	0.00	0.00	April 28	2.10	0.00	2.10
May 1	0.05	0.00	0.05	May 5	4.17	0.00	4.17
May 6	1.93	0.00	1.93	May 12	3.28	0.00	3.28
May 13	6.32	0.00	6.32	May 19	0.61	0.00	0.61
May 20	6.60	0.00	6.60	May 26	1.45	0.00	1.45
May 27	5.84	0.00	5.84	June 2	2.31	0.00	2.31
June 3	0.10	0.00	0.10	June 9	1.22	0.00	1.22
June 10	1.96	0.00	1.96	June 16	4.42	0.00	4.42
June 17	1.52	0.00	1.52	June 23	0.38	3.81	4.19
June 24	0.15	0.00	0.15	June 30	0.00	3.81	3.81
July 1	0.41	1.91	2.32	July 1	0.05	0.00	0.05
July8	0.05	1.27	1.32	July 7	1.93	1.91	3.84
July 15	1.14	1.91	3.05	July 14	0.00	3.18	3.18
July 22	0.28	0.00	0.28	July 21	4.62	1.91	6.53
July 29	4.44	0.00	4.44	July 28	4.88	0.00	4.88
Aug 5	2.79	1.91	4.70	Aug 4	0.66	0.00	0.66
Aug 12	3.76	0.00	3.76	Aug 11	8.48	0.00	8.48
Aug19	4.93	0.00	4.93	Aug 18	6.63	0.00	6.63
Aug 26	3.10	0.00	3.10	Aug 25	0.02	0.00	0.02
Sept 2	2.46	0.00	2.46	Sept 1	0.69	0.00	0.69
Sept 9	2.51	0.00	2.51	Sept 8	0.00	1.91	1.91
Total	58.67	7.00	65.67	Total	54.17	16.53	70.70

†Automated Montcalm Research Farm Weather Station

Ancillary soil moisture information was obtained with a TDR (Time Domain Reflectometry, Trime, Imko) 3-rod, 160 mm probe, that uses an electromagnetic pulse to determine soil moisture content. Four measurements per plot, two perpendicular and two parallel to the row, were taken weekly throughout the 2001 field season. Calibration was performed against the volumetric water content of samples taken from the Experiment Station, Range 1 site, and the Deaner Rd. (2001) field. Four cores per plot were pulled and divided into four equal depths of 5.0 cm each. Gravimetric water content and bulk density were determined from which the volumetric water content was derived. A simple linear regression model (SAS Inst., version 8.2) revealed that the TDR measurements were reliable 64% of the time at the Experiment Station and 84% of the time at the Deaner Rd (2001) field when three depths, 5 to 10, 10 to 15, and 15 to 20 cm, were combined. The cobbly nature of the soil at the Experiment Station may have caused wave interruption which reduced reliability at that location. In 2002, measurements of soil moisture were reduced to two parallel measurements per plot. Sampling was terminated in July due to mechanical problems with the equipment.

Harvest at the Experiment Station took place on September 13, in both years. Deaner Rd. and Masters Rd. fields were harvested on August 23, 2001 and August 20, 2002, respectively. Carrots, at all locations, were dug by hand from the center 3.0 m of the middle row of the middle bed of each plot. Whole plants were harvested from each plot and weighed in bulk. The tops were separated from the roots using a portable squeeze-roll topper, and subsampled. The roots were graded according to marketable size: #1 > 5/8 inch to 1½ inch diameter at the shoulder, jumbo > 1½ inch, and small < 5/8 inch. Culls were roots that were misshaped, cracked or infected. Graded roots were weighed, counted, and subsampled. Top and root subsamples were subsequently weighed before drying at 60°C. Dried samples were weighed again, ground and analyzed for total N concentration using the Kjeldahl Method. Subsamples were used to determine the total dry matter of tops and roots. Certain errors in recording dry weight required the use of estimated moisture content to determine dry matter in tops at the Experiment Station in 2001, and to determine dry matter in tops and roots at Sandyland 2002. Michigan State University Plant and Soil Nutrient Laboratory performed the chemical analyses.

Statistical analysis was performed using regression models and analysis of variance (SAS Inst., version 8.2).

Results and Discussion

Soil N Availability and Plant Uptake

All data were normally distributed as evidenced by the Shapiro-Wilk test and residual plots. Extreme outliers, defined by SAS Univariate procedure (SAS Inst., version 8.2), were eliminated. Over 6000 measurements were analyzed and 12 were removed as outliers. The deep fibrous root system of the carrot crop (Warncke, 1996) used not only the N applied but generally drew down the residual NO_3^- - N from the previous potato crop, when N was applied early enough before harvest. Total plant uptake resulted in accumulation of more N than was thought available in the soil. Only N applied at the rate of 180 kg ha^{-1} resulted in available N in excess of plant uptake. Nitrogen uptake by the plants responded to treatments, and as the amount of applied N increased the amount of unaccounted for N decreased (Table 3). The high level of indigenous N in 2001 and other unexpected sources of N, described below, may in part explain the reason that results did not show more separation between treatments.

Table 3. Nitrogen activity in the soil including initial residual levels in the top 30 cm, applications, and ending residual levels compared to N uptake by plants and carrot root yield. Mean separation of plant uptake of N as compared to N treatments. Linear regression analysis as used to compare plant uptake of N with available N.

Initial Residual	Urea Applied	NO_3^- from water†	Available	Ending Residual	Uptake by Plants: Tops	Roots	Total	ΔN = Available – (Uptake + residual)	Root Yield
---	---	---	Nitrogen kg ha^{-1}	---	---	---	---	---	Mg ha^{-1}
			Montcalm Experiment Station 2001/Diamond Cut						
45.7	45	14.4	105.1	34.9	60.9b	67.4	128.3b	-58.1a	45.2
49.2	90	14.4	153.6	27.5	80.7ab	84.2	164.9ab	-38.8ab	53.3
52.4	135	14.4	201.8	40.7	99.5a	81.3	180.8a	-19.7ab	47.5
44.3	180	14.4	238.7	60.0	84.7ab	81.3	166.0ab	12.7b	46.2
p-value					0.03	ns	0.01	0.01	
r^2					0.38*	0.22	0.37*	0.52**	
			Sandyland (Deaner Rd) 2001/Asgrow B1, Prime Cut 59						
18.1	45	n/a	63.1	26.8	49.3b	50.3b	99.6b	-63.3a	47.8
18.5	90	n/a	108.5	25.3	61.7ab	63.5ab	125.2ab	-42.0ab	51.7
21.9	135	n/a	156.9	26.7	71.5ab	71.7ab	143.2a	-13.0bc	53.4
17.7	180	n/a	197.7	24.5	80.2a	73.6a	153.8a	19.4c	49.9
p-value					0.02	0.03	0.007	0.0004	
r^2					0.50**	0.49**	0.59***	0.78***	
			Montcalm Experiment Station 2002/Diamond Cut						
15.2	45	34.0	94.2	24.1	74.1	79.2	153.3	-83.2a	54.4
16.2	90	34.0	140.2	24.2	99.5	78.6	178.1	-62.1a	50.1
18.0	135	34.0	187.0	30.5	93.2	88.9	182.1	-25.6ab	54.2
16.9	180	34.0	230.9	34.0	103.3	84.9	188.2	8.7b	52.2
p-value					ns	ns	ns	0.003	
r^2					0.14	0.09	0.19	.67***	
			Montcalm Experiment Station 2002/Goliath						
15.9	45	34.0	94.9	19.3	77.8	73.6	151.4	-75.8a	59.7
13.1	90	34.0	137.1	23.5	87.9	83.2	171.1	-57.5ab	55.6
20.4	135	34.0	189.4	29.9	82.2	99.7	181.9	-22.4bc	61.1
18.4	180	34.0	232.4	37.0	99.3	93.5	192.8	2.6c	58.5
p-value					ns	ns	ns	.002	
r^2					0.18	0.29*	0.35	0.85***	
			Sandyland (Masters Rd) 2002/Sugar Snax						
16.2	20.4	n/a	36.6	16.5	70.3	39.9	110.2	-90.1a	34.8
12.1	59.1	n/a	71.2	15.0	95.1	41.3	136.4	-80.2ab	30.4
14.0	97.9	n/a	111.9	16.8	81.4	48.3	129.7	-34.6ab	40.3
13.1	136.5	n/a	149.6	21.8	106.6	50.6	157.2	-29.4b	37.0
p-value					ns	ns	ns	0.02	
r^2					0.21	0.15	0.28*	0.49**	

† NO_3^- - N from irrigation water was calculated based on approximate rate of 20.8mg NO_3^- - N L^{-1}.
Mean values with the same letters are not significantly different at $p \leq 0.05$.
ns = Overall F-value is not significant.
r^2: Correlation of Available N to plant uptake resulting from regression analysis.
* ** *** Significance of overall F-values at $p < 0.05$, 0.01, 0.001, respectively.

In 2001, at the Experiment Station, several confounding factors contributed to the somewhat unpredictable responses by carrot plants to N treatments. Residual N in 2001 from a previous crop was relatively high at approximately 45 to 53 kg ha^{-1} (Table 3), predominantly in the form of NO_3^- (Table 4). At least 10 of the 16 plots (2 ½ reps) of the Diamond Cut variety were subjected to additional irrigation from an adjacent grower's field that may have contained unknown quantities of NO_3^-. Experiment Station wells contained from 17 to 21 mg L^{-1} NO_3^- - N that added approximately 14.4 kg ha^{-1} NO_3^- - N to the crop in 2001 and 34.0 kg ha^{-1} NO_3^- - N in 2002 through the irrigation water. The unscheduled additional N raised even the lower treatments, at the Experiment Station, close to the seasonal MSU recommendation for carrot of 112 kg ha^{-1} (Warncke et al., 1992), and the remaining treatments well above planned N levels. Nitrogen content of the irrigation water at Sandyland was unknown; however, Table 3 shows plant uptake in excess of known availability.

In 2001, N uptake was divided fairly equally between tops and roots at both the Experiment Station and the Sandyland location. Although tops generally produce greater biomass than roots (White and Strandberg, 1978), only treatments 3 (135 kg ha^{-1}) and 4 (180 kg ha^{-1}) at the Experiment Station and treatment 4 at Sandyland showed greater N accumulation in the tops than the roots. At the Experiment Station, only the tops showed significant correlation to the N treatments, while at Sandyland, both the tops and roots showed significance at $p \leq 0.05$. In 2002 tops generally accumulated more N than roots (Table 3), but N uptake was not significantly correlated to treatments in either the tops or the roots.

When N was applied at least 35 days before harvest (Table 4, 2001 Exp. Stn.), residual NO_3^- - N in the soil, and total residual N as well, was reduced below elevated residual levels from the previous crop. Only where N was applied at the rate of 180 kg ha^{-1} did the residual N exceed the levels at planting across the four replications (Table 4).

Table 4. Comparison of beginning of season residual N with end of season residual N in the soil derived with KCl extractant.

Urea	Initial Residual N from previous crop			Residual N following carrot harvest		
Applied	NO_3^- - N	NH_4^+ - N	Total	NO_3^- - N	NH_4^+ - N	Total
kg ha^{-1}	------------	------------	------------kg ha^{-1}	------------	------------	------------
			Montcalm Experiment Station 2001/Diamond Cut			
45	39.1	6.6	45.7	7.6	27.3	34.9
90	42.3	6.8	49.1	3.7	23.7	27.5
135	44.8	7.6	52.4	15.2	25.3	40.7
180	38.9	5.5	44.4	34.4	25.6	60.0
			Sandyland (Deaner Rd) 2001/Asgrow B1 Prime Cut 59			
45	8.1	10.1	18.2	3.6	23.2	26.8
90	7.4	11.1	18.5	3.7	21.6	25.3
135	8.1	13.9	22.0	3.7	22.8	26.7
180	7.9	9.9	17.8	2.2	22.3	24.5
			Montcalm Experiment Station 2002/Diamond Cut			
45	12.4	2.8	15.2	9.9	14.2	24.1
90	11.6	4.6	16.2	11.9	12.3	24.2
135	12.9	5.1	18.0	16.9	13.5	30.5
180	12.2	4.7	16.9	22.8	11.1	34.0
			Montcalm Experiment Station 2002/Goliath			
45	11.6	4.3	15.9	3.6	15.7	19.3
90	9.5	3.4	12.9	9.0	14.6	23.5
135	14.4	5.9	20.3	15.2	14.7	29.9
180	12.5	5.8	18.3	22.2	14.8	37.0
			Sandyland (Masters Rd) 2002/Sugar Snax 54			
20	13.7	2.6	16.3	1.2	15.2	16.5
59	9.6	2.5	12.1	1.1	13.9	15.0
98	12.0	2.0	14.0	1.3	15.5	16.8
136	10.6	2.5	13.1	2.4	19.4	21.8

In 2001, at Sandyland, N was applied only 23 days before harvest and even though residual NO_3^- - N was reduced, the total residual N was higher at harvest than at planting (Table 4). In 2002, at all locations, the last treatment was applied 20 days before harvest. Here too, while residual NO_3^- -N was generally reduced in all but the plots representing rates of 135 and 180 kg ha^{-1}, the total residual N remained higher than initial levels. According to Warncke (1996) N applications too close to harvest may contribute to excess residual N such as experienced here. When N was applied at least 62 days before harvest, available N levels were reduced to near background levels (Warncke, 1996). In this study, available N would have been reduced to below initial levels if the last application had occurred earlier in the season or the carrots had been allowed to continue development for a later harvest date.

N Treatments vs Petiole Response

The % N content of the petioles sampled throughout the growing season is shown in Table 5. In both 2001 and 2002, % N generally responded to the amount of N applied as of each date petiole samples were taken at both the Experiment Station and Sandyland; however, not all resulted in significant differences between treatments.

In addition, petiole sap NO_3^- generally responded to the N treatments, including N uptake in addition to that required for maximum yield (Tables 6 and 7). When compared to % N content, petiole sap NO_3^- was significantly correlated at $r^2 > 0.40$ on nine of the 15 sampling dates covering the two year period (Tables 6 and 7), even when neither parameter reflected positive response to N treatments. In a previous study Warncke (1996) indicated that petiole sap NO_3^- content is an apparent good indicator of the N status of the carrot plant. Petiole sap NO_3^- using the Cardy Meter, a quick in-field NO_3^- test, was shown to reflect the N status of the carrot plant in this study as well as earlier studies by Warncke (1996) and Hochmuth (1994). Just prior to harvest, at the Experiment Station, % N and petiole sap NO_3^- generally indicated that N uptake and

Table 5. Mean separation between treatments of % N in carrot petioles sampled on the indicated dates. Average yield per N treatment, from each specified location, listed for comparison to % N in petioles.

Montcalm Experiment Station 2001/Diamond Cut
Planting date = 5/8/01 Harvest date = 9/13/01

Trt[†]	Root Yield	July 20 (73)[‡]	July 25 (78)	Aug 15 (99)	Sept 11 (126)
kg ha^{-1}	Mg ha^{-1}	-----% N (TKN)-----			
45	45.2	1.56	1.26	0.65b	0.73c
90	53.3	1.62	1.32	0.84ab	0.93bc
135	47.5	1.57	1.35	0.88ab	1.03ab
180	46.2	1.72	1.30	1.00a	1.20a
p-value		ns	ns	0.01	0.0002

Sandyland (Deaner Rd) 2001/Asgrow B1 Prime Cut 59
Planting date ~ 4/20/01 Harvest date = 8/23/01

Trt	Root Yield	July 11 (82)	July 19 (90)	Aug 1 (103)
kg ha^{-1}	Mg ha^{-1}	-----% N (TKN)-----		
45	47.8	0.44	0.25c	0.27
90	51.7	0.54	0.45bc	0.35
135	53.4	0.65	0.58ab	0.32
180	49.9	0.61	0.80a	0.41
p-value		ns	0.0002	ns

Montcalm Experiment Station 2002/Diamond Cut
Planting date = 5/7/02 Harvest date = 9/13/02

Trt	Root Yield	July 25 (76)	Aug 22 (104)	Sept 9 (122)
kg ha^{-1}	Mg ha^{-1}	-----% N (TKN)-----		
45	54.4	0.76b	0.50c	0.62
90	50.1	0.88ab	0.56bc	0.69
135	54.2	0.89ab	0.66ab	0.76
180	52.2	0.96a	0.72a	0.77
p-value		0.02	0.001	ns

Montcalm Experiment Station 2002/Goliath
Planting date = 5/7/02 Harvest date = 9/13/02

Trt	Root Yield	July 25 (76)	Aug 22 (104)	Sept 9 (122)
kg ha^{-1}	Mg ha^{-1}	-----% N (TKN)-----		
45	59.7	0.83	0.42b	0.77b
90	55.6	0.87	0.57a	1.02ab
135	61.1	0.90	0.59a	0.96ab
180	58.5	1.02	0.66a	1.19a
p-value		ns	0.002	0.009

Sandyland (Masters Rd) 2002/sugar Snax 54
Planting date ~ 4/20/02 Harvest date = 8/20/02

Trt	Root Yield	July 25 (96)	Aug 19 (121)
kg ha^{-1}	Mg ha^{-1}	-----% N (TKN)-----	
20.4	34.8	0.58b	0.63
59.1	30.4	0.72b	0.64
97.9	40.3	0.69b	0.59
136.5	37.0	0.99a	0.58
p-value		0.002	ns

[†]Trt = Treatment

[‡]Number in parenthesis represents days after planting.

Mean values with the same letters are not significantly different at $p \leq 0.05$.

Table 6. Linear regression results of petiole sap NO_3^- - N vs Total N (TKN) of dried petioles sampled on various dates during the 2001 season. N available was as of the petiole sampling date. Values shown were averaged by treatment.

Montcalm Experiment Station 2001/Diamond Cut								
N† Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N
---July 20---			---July 25---			---Aug 15---		
Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%
101.0	2600	1.56	101.0	2250	1.26	105.1	720	0.65
126.9	2600	1.62	126.9	3175	1.32	153.6	1240	0.84
152.5	3150	1.57	152.5	2475	1.35	201.8	1725	0.88
166.9	3075	1.72	166.9	2475	1.30	238.7	1975	1.00
	$r^2 = 0.06$			$r^2 = 0.31^{*}$			$r^2 = 0.84^{***}$	

Montcalm Experiment Station 2001/Diamond Cut		
N Avail	Sap NO_3^-	Total N
---Sept 11---		
Kg ha^{-1}	mg L^{-1}	%
105.1	640	0.73
153.6	1220	0.93
201.8	2200	1.03
238.7	2800	1.20
	$r^2 = 0.75^{***}$	

Sandyland (Deaner Rd) 2001/Asgrow B1, Prime Cut 59								
N Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N
---July 11---			---July 19---			---Aug 1---		
Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%
63.1	294	0.44	63.1	242	0.25	63.1	300	0.27
96.9	327	0.54	96.9	380	0.45	108.5	287	0.35
122.7	502	0.65	122.7	595	0.58	156.9	262	0.32
140.9	487	0.61	140.9	762	0.80	197.7	330	0.41
	$r^2 = 0.69^{***}$			$r^2 = 0.72^{***}$			$r^2 = 0.004$	

†Estimated N available at the specific sampling date including residual from the previous crop, treatment applications, and an estimate of NO_3^- - N from the irrigation water.
*,**,*** Significance of overall F-values at $p \leq 0.05$, 0.01, 0.001, respectively.

storage in petioles responded to N treatments. Results were less favorable at the Sandyland locations.

In 2001, N uptake in harvested tops generally agreed with % N in petiole and petiole sap NO_3^-, except at the Experiment Station where treatment 3 (135 kg ha^{-1}) had

Table 7. Linear regression results of petiole sap NO_3^- - N vs Total N (TKN) of dried petioles sampled on various dates during the 2002 season. N available was as of the petiole sampling date. Values shown were averaged by treatment.

Montcalm Experiment Station 2002/Diamond Cut								
N† Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N
July 25			Aug 22			Sept 9		
Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%
45.2	1470	0.75	67.2	530	0.50	94.2	410	0.62
80.0	1550	0.88	108.0	648	0.56	140.2	790	0.69
115.4	1975	0.89	149.0	960	0.66	187.0	1074	0.76
147.8	1875	0.96	187.0	1233	0.72	230.9	1375	0.77
	$r^2 = 0.06$			$r^2 = 0.43^{**}$			$r^2 = 0.23$	

Montcalm Experiment Station 2002/Goliath								
N† Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N
July 25			Aug 22			Sept 9		
Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%
46.0	2225	0.83	68.4	290	0.42	94.9	437	0.77
76.8	2600	0.87	104.8	845	0.57	137.1	797	1.02
117.7	2550	0.90	151.3	815	0.59	189.4	670	0.96
149.3	3550	1.02	188.5	1575	0.66	232.4	1310	1.19
	$r^2 = 0.0$			$r^2 = 0.70^{***}$			$r^2 = 0.50^{**}$	

Sandyland (Masters Rd) 2002/Sugar Snax 54					
N Avail	Sap NO_3^-	Total N	N Avail	Sap NO_3^-	Total N
July 25			Aug 19		
Kg ha^{-1}	mg L^{-1}	%	Kg ha^{-1}	mg L^{-1}	%
16.2	453	0.58	36.6	230	0.63
45.7	378	0.72	71.2	313	0.64
81.2	383	0.69	112.9	273	0.59
113.9	943	0.99	149.6	315	0.58
	$r^2 = 0.51^{**}$			$r^2 = 0.14$	

†Estimated N available at the specific sampling date including residual from the previous crop, treatment applications, and an estimate of NO_3^- - N in the irrigation water.

*, **, *** Significance of overall F-values at $p \leq 0.05$, 0.01, 0.001, respectively.

the highest accumulation of N instead of the treatment 4 as reflected in the petiole results (Tables 6 and 8). At Sandyland, N accumulation in tops reflected the amount of N applied; however, results of late season petiole analyses were mixed. In 2002 treatment 1 (45 kg ha^{-1} N) resulted in the lowest accumulation of N, while treatment 4 (180 kg ha^{-1})

resulted in the highest, but intermediate treatment levels varied (Table 8).

Treatments vs N Uptake in Harvested Dry Matter and Yield

Dry matter and N uptake in tops were significantly correlated (Table 8) at almost all locations. At the Experiment Station 2001, dry matter and N uptake increased with treatment, and treatment 3 resulted in the highest amount of dry matter accumulation. Even though % N and petiole sap NO_3^- showed that carrot continued to accumulate more N through treatment 4 (Table 6), it did not increase dry matter indicating excessive uptake of N by the plant (Table 8). Dry matter and N uptake in tops as well as % N and petiole sap NO_3^- at Sandyland increased with treatment amounts through treatment 4. Available N in treatment 4 at Sandyland was about the same as treatment 3 at the Experiment Station, where higher amounts of N had been available at the beginning of the season. There, the carrot crop generally reduced available soil N below initial levels. With the 2002 season end at Sandyland, dry matter content of tops related to N uptake but was not significantly correlated. Top dry matter and the N uptake of Goliath carrots at the Experiment Station were significantly correlated, but with an inverse trend that may have been due, in part, to foliar blight in the Goliath variety. N accumulation in tops generally increased with treatment but permanent damage from the blight reduced the amount of dry matter and affected the positive correlation to N uptake. Generally, the N treatments seemed to influence top growth to a greater extent than roots, as indicated by Warncke (1996).

Only at the Experiment Station in 2001 was dry matter (Table 8) in roots nominally influenced by N treatment. There, and in the Goliath variety and at Sandyland

Table 8. Mean N uptake in tops and roots compared to dry matter and root yield using regression analysis. Mean available N compared to root:shoot ratio using regression analysis. Significance of treatment differences in dry matter, root: shoot ratio, and root yield determined using analysis of variance.

trt†	Available N	-------N Uptake------		------Dry Matter-----		Root: Shoot Ratio	Fresh Root Yield
		Tops	Roots	Tops	Roots		
--------------------kg ha^{-1}--------------------				---------------------Mg ha^{-1}---------------------			
Montcalm Experiment Station (2001)/Diamond Cut (128 days‡)							
45	105.1	60.9	67.4	3.4b	4.9a	1.5a	45.2
90	153.6	80.7	84.2	4.3a	5.8a	1.3a	53.3
135	201.8	99.5	81.3	4.3a	5.1a	1.2a	47.5
180	238.7	84.7	81.3	4.1ab	5.0a	1.2a	46.2
p-value				0.026	0.045	0.04	0.06
Regression (r^2)				0.48^{**}	0.59^{***}	0.38^{**}	0.51^{**}
Sandyland (Deaner Rd.) 2001/ Asgrow B1, Prime Cut 59 (125 days)							
45	63.1	49.3	50.3	4.6b	6.1	1.3a	47.8
90	108.5	61.7	63.5	5.1ab	6.8	1.3a	51.7
135	156.9	71.5	71.7	6.2ab	6.3	1.0b	53.4
180	197.7	80.2	73.6	6.4a	5.8	0.9b	49.9
p-value				0.029	ns	0.001	ns
Regression (r^2)				0.36^{*}	0.10	0.63^{***}	0.37^{*}
Montcalm Experiment Station (2002)/Diamond Cut (129 days)							
45	94.2	74.1	79.2	4.7	5.5	1.2	54.4
90	140.2	99.5	78.6	6.0	5.3	1.0	50.1
135	187.0	93.2	88.9	5.0	5.2	1.0	54.2
180	230.9	103.2	84.9	5.6	5.2	0.9	52.2
p-value				ns	ns	ns	ns
Regression (r^2)				0.73^{***}	0.19	0.06	0.27^{*}
Montcalm Experiment Station (2002)/Goliath (129 days)							
45	94.9	77.8	73.6	5.8	5.8	1.0	59.7
90	137.1	87.9	83.2	5.7	5.3	0.9	55.6
135	189.4	82.2	99.7	5.5	6.2	1.2	61.1
180	232.4	99.3	93.5	5.5	5.4	1.0	58.5
p-value				ns	ns	ns	ns
Regression (r^2)				0.37^{*}	0.29^{*}	0.02	0.14
Sandyland (Masters Rd) 2002/ Sugar Snax 54 (122 days)							
45	36.6	70.3	39.9	6.2	4.3	0.7	34.8
90	71.2	95.1	41.3	7.7	3.8	0.5	30.4
135	111.9	81.4	48.3	7.4	5.1	0.7	40.3
180	149.6	106.6	50.6	7.8	4.5	0.6	37.0
p-value				ns	ns	ns	ns
Regression (r^2)				0.23	0.47^{**}	0.004	0.37^{**}

† trt = treatment

‡ Number of days from planting to harvest.

Mean values with the same letters are not significantly different at $p \leq 0.05$.

ns = Overall F-value is not significant.

$^{*, **, ***}$ Significance of overall F-values at $p \leq 0.05$, 0.01, 0.001, respectively.

in 2002, correlation was significant between N uptake and dry matter accumulation in roots. At the Experiment Station, in 2001and 2002 the Diamond Cut and Goliath varieties maximized N uptake in the roots at between 153 and 189 kg ha^{-1} available N. The large range is due to the inclusion of estimated NO_3^- - N from irrigation water of up to 34.0 kg ha^{-1}. Root yield increased with N applied and the maximum yield, which was significantly correlated to N uptake, also ranged between 153 to 189 kg ha^{-1} N. In both years, the Sandyland carrot crops were planted at a high population rate for the "cut-and-peel" market. While in 2001, yield was maximized at 157 kg ha^{-1}, similar to the Experiment Station, N accumulation in the roots continued to increase with total available N, up to almost 198 kg ha^{-1}. In 2002, the carrots were harvested before the last planned N application occurred so that the highest available N was 150 kg ha^{-1}. It is believed that the 2002 yield at Sandyland would have been similar to the others if the carrots had not been harvested until after the last scheduled N application, and the season extended to match the season length of the other locations (Table 8). At both Sandyland locations the roots accumulated more N than was used for biomass production, similar to the Warncke (1996) study. Results at Sandyland reflect treatments applied to research plots within the field; they are not indicative of N applied to the commercial areas.

The tops continued to accumulate more N at the excessive 180 kg ha^{-1} rate (treatment 4) at all locations except the Experiment Station 2001, even though it was not reflected in the yield as previously shown by Warncke (1996) and Hochmuth et al.(1999). At Sandyland, 2002, maximum yield occurred at 112 kg ha^{-1} due, at least in part, to reduced applications. The amount of N applied in both treatments 3 and 4 were higher than the MSU recommendation of 112 kg ha^{-1} (Warncke et al., 1992). According to

Hochmuth (1999) additions of N in excess of that required for maximum root production only served to increase shoot growth. Generally, when N is the limiting nutrient, increasing the N supply enhances both root and shoot, but mostly shoot growth that results in a decreasing root:shoot ratio (Marshner, 1998). Hochmuth (1999) noted that in carrot once maximum yield has been attained, a decreasing root:shoot ratio resulting from additional N applications, could result in potential reduction in yield and profit from excess N fertilization. Table 8 shows where the excess N accumulated in the shoots, it resulted in excessive top growth at three of the four locations affected. At the Sandyland locations, top growth was maximized in treatment 4, with a decreasing root:shoot ratio. The root:shoot ratio also fell in the 2002 Experiment Station plots, as the result of either a decreased root dry matter or increased shoot growth (dry matter).

Carrot yield did not significantly respond to N treatments (Table 9). Maximum yield was attained with treatment 3 at all locations except the Experiment Station in 2001. At that site, treatment 2, which corresponded to the amount of available N in treatment 3 at the other locations, produced the highest yield. Diamond Cut and Prime Cut 59, both Imperator type varieties, maximized yield at about 53 to 54 Mg ha^{-1}. If Sugar Snax 54, also an Imperator type variety, would have had a comparable season length and N treatments, it too may have yielded as much as the other Imperator type varieties. The Danvers type variety, Goliath, yielded 61 Mg ha^{-1}. The majority of jumbo roots, greater than 1½ inches in diameter at the shoulder, were yielded by Goliath at 35-45% of the total yield. Diamond Cut yielded 3-15% jumbos. The Prime Cut 59 and Sugar Snax 54 varieties were planted at a high population rate for the cut and peel market, and as expected, did not yield any jumbo roots. Yield of Diamond Cut and Sugar Snax was

Table 9. 2001 and 2002 carrot root yield by grade and percent of the total.

N Applied	Jumbo†	#1†	Small†	Cull†	Total Yield	Jumbo	#1	Small	Cull
	--Grade--					--Grade--			
	--Mg ha^{-1}--					--% of total yield--			
	Montcalm Experiment Station (2001)/ Diamond Cut Seeding rate: 204,000/A								
45	6.6	28.5	1.0	9.1	45.2	0.15	0.63	0.02	0.20
90	6.9	35.9	1.0	9.5	53.3	0.13	0.67	0.02	0.18
135	7.1	27.6	0.9	11.9	47.5	0.15	0.58	0.02	0.25
180	7.1	29.6	1.4	8.1	46.2	0.15	0.64	0.03	0.18
	Sandyland (Deaner Rd) 2001/Asgrow BI, Prime Cut 59 Seeding rate 870,000/A								
45	0.00	6.0	41.8	0.00	47.8	0.00	0.13	0.87	0.00
90	0.00	12.9	38.8	0.00	51.7	0.00	0.25	0.75	0.00
135	0.00	11.1	42.3	0.00	53.4	0.00	0.21	0.79	0.00
180	0.00	7.2	42.7	0.00	49.9	0.00	0.14	0.86	0.00
	Montcalm Experiment Station (2002)/Diamond Cut Seeding rate: 450,000/A								
45	1.5	39.1	8.9	4.9	54.4	0.03	0.72	0.16	0.09
90	2.7	32.4	8.8	6.2	50.1	0.05	0.65	0.18	0.12
135	1.6	36.4	10.8	5.4	54.2	0.03	0.67	0.20	0.10
180	1.8	35.1	9.8	5.5	52.2	0.03	0.67	0.19	0.11
	Montcalm Experiment Station (2002)/Goliath Seeding rate: 450,000/A								
45	20.9	20.5	14.7	3.6	59.7	0.35	0.34	0.25	0.06
90	19.8	20.5	11.7	3.6	55.6	0.36	0.37	0.21	0.06
135	26.7	17.9	12.4	4.1	61.1	0.44	0.29	0.20	0.07
180	23.8	17.3	12.6	4.8	58.5	0.41	0.30	0.22	0.08
	Sandyland (Masters Rd) 2002/Sugar Snax Seeding rate: 750,000/A								
45	0.00	23.4	10.4	1.0	34.8	0.00	0.67	0.30	0.03
90	0.00	17.0	12.3	1.1	30.4	0.00	0.56	0.40	0.04
135	0.00	25.2	13.1	2.0	40.3	0.00	0.63	0.33	0.05
180	0.00	24.9	10.9	1.2	37.0	0.00	0.67	0.29	0.03

†Jumbo = >1½ in at the shoulder, #1 = > 5/8 in to 1½, small = 5/8 in and smaller, culls = misshaped, cracked or infected roots.

dominated by the #1 grade, between 5/8 inch and 1½ inch, ranging from 56 to 72% of the total yield. The Goliath variety had a fairly equal split between jumbo and #1. The Sandyland 2001 location was planted with an excessively high population rate; most of the roots were small at 5/8 inch and smaller. The culls were a higher percentage of total yield in Diamond Cut than other varieties, as high as 25% in treatment 3, 2001. Culls consisted primarily of misshaped roots, possibly resulting from cobbly soil conditions at the Experiment Station and disturbance of the roots caused by intense early season rains.

Conclusions

Carrot response to the planned N treatments as applied was limited and confounded by extraneous variables discussed throughout the chapter. Only in 2001 did total N uptake in the plants respond to treatments. Petiole samples provided the best in-season correlation to treatments. However, the carrot crop did respond to the conditions and certain significant correlations and lessions were provided in the outcome.

Maximum N uptake in the storage roots correlated with maximum yield at the Experiment Station. Only in the experimental plots at Sandyland did N continue to accumulate beyond maximum yield, even though it did not contribute to biomass production. Timing of the last N application could have contributed to the excessive storage of N and points out the importance of applying N early enough to avoid excess accumulation in the roots, as shown in Warncke (1996). At the Experiment Station 2001, where N had been applied at least 35 days before harvest, dry matter content significantly correlate to N uptake. Better timing of N applications may have promoted better tissue growth with realized economic benefits at harvest.

Total plant uptake exceeded amounts estimated as available to the crop at all treatment levels except treatment four. Nitrogen that was unaccounted for may have in part become available through mineralization of past crop residue. Initial soil sampling below 30 cm prior to N applications may have revealed additional N that became available to the carrot crop once the deep fibrous root system extended beyond the 30 cm.

Although tops are not considered part of yield, their health is important in certain harvesting operations where tops are used to help lift the roots out of the soil. If N applications are necessary toward season end, foliar applications may be enough to boost the health of the tops without adding nutrients to the soil. In 2002 tops at the Experiment Station received an estimated 34.0 kg ha^{-1} N through irrigation compared to 14.4 kg ha^{-1} N in 2001. Comparison of the root:shoot ratio for the two year study for the Diamond Cut variety indicated a positive influence from the foliar applications. Foliar applications of N have been known to aid plant vigor during times of stress (Warncke, 2000), and the N is absorbed very quickly (Tremblay et al., 2001).

Total petiole N and petiole sap NO_3^- have been shown to be good indicators of the in-season N status of the carrot crop (Warncke, 1996). Results of analyses on samples collected several times during the two seasons indicated that petiole sampling significantly reflected the amount of N applied in about 60% of the samples, even where foliar diseases were a problem. The remaining samples, although lacking significance, generally reflected the amount of N applied. N applied through irrigation water may have compromised differences between planned applications. Percent N was still a good indicator of N status in this study, and petiole sap NO_3^- , using the Cardy Meter, a quick in-field NO_3^- test performed as well as total petiole N analysis.

In this study, carrot generally drew down N in the profile when N was applied at least 35 days prior to harvest. If treatments were applied closer to harvest, the carrot crop did not have adequate time to take up the N applied. Tremblay et al. (2001) experimentally determined for carrot that residual N in excess of 30 kg ha^{-1} was excessive.

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Chapter II

Spectral Measurements of the Carrot Canopy as Related to Nitrogen Status of the Crop

Introduction

As early as 1952, Moss and Loomis measured absorptance spectra of individual leaves using an integrating sphere (Moss and Loomis, 1952). By 1956, the pioneering research of Colwell was detecting field-wide loss of plant vigor to disease from the lofty view of aerial photography (Shanahan et al., 2001). In 2002, Oklahoma State University (OSU) scientists perfected the Greenseeker, an integrated sensing and application system. This field-scale variable rate applicator, built in cooperation with Ntech Industries Inc., calculates N rates in fractions of a second, using remote sensing, and variably applies N as it travels across the field. It has already been shown to increase yield and decrease N applications (Dept. of Plant and soil Sciences, OSU, 2004).

Reduction of N applications for the purpose of protecting groundwater from leaching nitrogen (N) (Blackmer and Schepers, 1994; Flowers et al., 2003a) and promoting economic stability through efficient use (Flowers et al., 2001; Flowers et al., 2003b) has been the focus of both research and equipment development. Soil properties, landscape position, and disposition of previous N applications cause available N for plant uptake to vary spatially (Flowers et al., 2003b). To address the question of efficient use, knowing that conditions vary spatially and temporally across fields, suggests that intensive sampling is necessary. The fundamental field element "defined as the area which provides the most precise measurement of the available nutrient and where the level of that nutrient changes with distance" is seldom larger than 1 m^2 (Dep. of Plant and Soil Sciences Oklahoma State University, 2004). Physical sampling of soil and tissue at such an intensive level is impractical (Aparicio et al., 2000; Blackmer et al., 1994) and compromises repeat sampling. Technological advancements, such as variable rate fertilizer applicators, made precision management on a large-scale possible, but created the need for better methods of assessing within-field variability. Remote sensing technology is making tremendous strides and seems to be the answer to the need for intensive sampling as described above. Remote sensing has made it possible to measure many plants at once for a variety of parameters (Blackmer et al., 1996a). Sensors such as the OSU Greenseeker, attached to variable rate applicators, have made real-time assessment of nutrient requirements with almost simultaneous application a reality. In addition to nutrient management, remote sensing may be used to monitor diseases and crop damage (Flowers et al., 2001). Automating measurements by mounting sensors on mobile overhead sprinkler systems may facilitate continuous monitoring and detection of changes in nutrient as well as water sufficiency. Early estimates of yield in wheat and corn have also been successful using remote sensing (Flowers et al., 2003a, 2003b).

Lillesand and Kiefer (2000) define remote sensing as both a science and an art. It is the gathering of information about an object, area, or phenomenon using a device not in contact with the target, and includes both the collection and analysis of the data (Lillesand and Kiefer, 2000). The discussion, herein, is limited to spectral reflectance data obtained from portable (hand-held) radiometers, and aerial photography.

Remote sensing is a spatial and temporal measurement. Spectral radiance collected at different dates provides different information about the system. Early season reflectance is primarily influenced by soil characteristics with different soils having different spectral characteristics. As the season progresses, plant characteristics increasingly dominate spectral information (Chang et al., 2003). Osborne et al. (2002) found that important wavebands used for predicting N content, biomass and grain yield change with sampling date and that such changes may be attributed to temporal variations in percent ground cover and growth stages. The energy incident on a crop canopy varies as well over the day and through the season as a function of the solar zenith angle (Epiphanio and Huete, 1994).

Surface reflectance, internal scattering, and attenuation of sun light by a leaf is greatly affected by its physical and chemical characteristics (Al-Abbas et al., 1974; Maas and Dunlap, 1989). Nutrient deficiencies cause visible abnormalities in pigmentation as a result of the reduction of leaf chlorophyll content, the size and shape of leaves, and the photosynthetic rate linked to the amount of absorbed radiation (Al-Abbas et al., 1974; Maas and Dunlap, 1989; Masoni et al., 1996), resulting in measurable changes in reflectance, absorptance and transmittance. For example, N treatment effects are attributed to differences in leaf area, crop biomass, soil cover, plant height, and chlorophyll concentration (Blackmer et al., 1996a), and interpretation of the information gathered is based on the knowledge of the interaction of electromagnetic radiation with the plant leaves and canopy (Maas and Dunlap, 1989). Chlorophyll and N concentration influence reflectance in the visible blue, green and red wavelengths, where a reduction in chlorophyll content results in increased reflectance. For example, N treatment at 45 kg ha^{-1} should result in higher visible canopy reflectance compared to a treatment at 135 kg ha^{-1}. Vegetative cover and vigor directly influence reflectance in the NIR (Flowers et al., 2003b). An increase in NIR reflectance is usually associated with increasing N. External and internal reflectance and pigment content (mostly chlorophyll) affect the extent of absorptance (Maas and Dunlap, 1989).

Many factors challenge the interpretation of spectral data at the ground and aerial level: weeds, diseases, insect damage, water stress, varietal differences, plant nutrition, soil background, sun angle, bidirectional information, and equipment irregularities (Flowers et al., 2003a; Al-Abbas et al., 1974). Interpreting the interaction of irradiance with canopy characteristics has been the focus of extensive research. Researchers have developed vegetation indices to account for or eliminate factors that confound parameters of interest by taking advantage of the high absorption of red wavelengths and the strong reflectance of the NIR portion of the spectrum by photoactive tissue in plants which is distinctive from soil and water (Wiegand et al., 1991). Several of the studies are described in the following section.

The first objective of this study was to determine which reflectance measurements correlated to various physical parameters typically used to evaluate the health of the carrot crop. The second objective was to determine if reflectance measurements could be used for in-season N management of healthy carrot tops.

Literature Review

Plant pigments are of particular interest, in remote sensing, because it may be possible to detect nutrient deficiency, salinity, stress, and other parameters at wavelengths influenced by plant pigments (Maas and Dunlap, 1989). The greatest differences in pigmentation are detected between 380 and 750 nm (Blackmer et al., 1994; Maas and

Dunlap, 1989). Maas and Dunlap (1989) using the spectral differences between normal, etiolated, and albino corn (*Zea mays* L.) leaves, identified the individual spectral effects of chlorophyll and carotenoid pigments, and the background cellular structure and water content. They observed large concentrations of chlorophyll and carotenoids in normal leaves that were totally absent from the albino leaves. The etiolated leaves contained intermediate levels of ß-carotene, the most abundant carotenoid pigment in higher plants (Maas and Dunlap, 1989). Their study showed that chlorophyll and carotenoid pigments controlled the visible optical properties in normal leaves, and that leaf reflectance in the visible band is controlled by absorption by the chlorophylls. The greatest absorptance (low reflectance) was observed at 430 and 670nm wavelengths similar to the absorptance peaks of extracted chlorophyll, which exhibits a sharp peak at 670nm (Maas and Dunlap, 1989). A gradual decrease of absorptance (increase in reflectance) between 482 and 550 nm is associated with carotenoids and was observed in both normal and etiolated leaves. The increase in absorptance (decrease in reflectance) between 550-670nm is attributed to "biological forms of chlorophyll" (Brown, 1972). Maas and Dunlap (1989) noted that wavelengths at 550 and 670nm were affected by a combination of carotenoid and chlorophyll pigments in corn. The optical properties of the etiolated leaves were dominated by carotenoids along with the background optical characteristics associated with the albino leaves. ß-carotene was the influencing factor in the visible band. The optical properties of albino leaves were dominated by the cell structure and water content (Maas and Dunlap, 1989). Without pigments to absorb the irradiance, albino leaves showed leaf reflectance similar to that observed in the NIR (800-1200nm) region: low absorptance resulting in high reflectance (Maas and Dunlap, 1989).

Thomas and Gausman (1977) reported that 550 nm, where there was relatively little absorption, was superior to 450 and 670 nm in relating leaf reflectance to either chlorophyll or carotenoid concentration for eight different crops. Blackmer et al. (1994), Blackmer et al. (1996a), and Masoni et al. (1996) also reported that the measure of reflectance at wavelengths showing relatively little absorption (550 nm) provided the most sensitive assessment of N status. N deficiencies showed little or no effect on reflectance from any of the corn hybrids at 450 or 650 nm, which suggests that either light was equally absorbed (even with deficiencies) or that some of the light was transmitted through the leaf (Blackmer et al., 1994). Reflectance of the green wavelengths peaks at 550 nm and is generally recognized as an indication of N status for many agronomic crops (Blackmer et al., 1994). The greatest reflectance consistently occurred with the lowest N rates because N deficiencies result in decreased amounts of leaf chlorophyll that absorbs less light and results in greater reflectance (Blackmer et al., 1994).

Other nutrients as well as N affect chlorophyll content and, therefore, the leaf spectra (Al-Abbas et al., 1974; Masoni et al., 1996). It is important to summarize some of these characteristics, especially in relation to N deficiency similarities. In corn, chlorophyll-a was greatly affected, in order, by Fe, Mg, and Mn deficiencies, and to a lesser extent by S deficiency. The order of severity of deficiency symptoms affecting chlorophyll content varies with species (Masoni et al., 1996). While Fe, S, Mg, and Mn all contributed to the reduction in chlorophyll that in turn resulted in decreased absorption and increased reflectance, there was no correlation between the chlorophyll content and mineral content. Lack of correlation may be due to the depleted uptake of other nutrients in addition to treatments (Masoni et al., 1996). However, chlorophyll content is highly correlated with leaf -N content (Wolfe et al., 1988; and Schepers et al., 1992). For each mineral deficiency, there was first a reduction of leaf chlorophyll concentration and then a decrease in spectral absorptance with a synergistic increase in reflectance. The best correlation between leaf chlorophyll concentration and reflectance, transmittance and absorptance was found at 555 and 700 nm where Fe, Mg, Mn, and S were deficient (Masoni et al., 1996). Blackmer et al. (1996a) found 550nm and 710nm better for detecting N deficiency than other wavebands.

Al-Abbas et al. (1974) studied the spectral effects of deficiencies of six nutrients including N. He found that in corn, N deficiency resulted in the lowest chlorophyll content followed in increasing order by Mg, S, K, Ca, and P, although, the highest reflectance was displayed by K followed in order by Mg, N, S, P, and Ca. Potassium deficient leaves had the lowest moisture content and were among the thinnest indicating that reflectance may be closely related to leaf thickness and moisture content in addition to pigment abnormalities. Maas and Dunlap (1989) noted that knowledge of leaf thickness and water content is essential for determination of pigment concentration from leaf reflectance at visible wavelengths. Walburg et al. (1982) and Maas and Dunlap (1989) also found that changes in external as well as cellular leaf structure, along with pigment concentration, affected the spectral reflectance resulting from N treatments. In a field study, Osborne (2002) noted that where P was deficient in corn there was an increase in anthocyanin production causing purpling at leaf margins. Anthocyanin strongly absorbs in the blue to green spectral region compared to the red spectral region. However, in a greenhouse study, Milton et al. (1991) noted that P deficient leaves of soybean plants grown in hydroponic solutions had higher reflectance in the green and yellow portion of the visible band. Along with the presence of anthocyanin, reflectance measurements indicated that NIR reflectance was important for predicting P stress during the early season driven by the internal cell structure, but N concentrations could be predicted throughout the growing season (Osborne et al., 2002). Al-Abbas et al. (1974) found that regardless of the deficiency, all deficient plants contained less chlorophyll than the control (normal). The results indicate that chlorophyll has a dominant influence on the spectral variation in the visible region of the spectrum. Variation at 550 nm seems to best indicate N status, but other nutrient deficiencies are also expressed in this region.

Near infrared (NIR), reflectance and transmittance from 750 to 1300 nm is generally associated with leaf structure and morphology (Al-Abbas et al., 1974). At 780 to 810 nm, NIR is particularly sensitive to the presence of amino acids ($R\text{-}NH^2$), the building blocks of protein, the presence or absence of which largely determine the N content of the plant (Dep. of Plant and Soil Sciences Oklahoma State University, 2004). As vegetative cover increases, NIR reflectance increases because multiple leaf layers increase light scattering and reflectance (Walburg et al., 1982). Absorption in the NIR region is characteristically lower than in the visible region of the spectrum. NIR reflectance has been used to predict nutrient concentration, yield and crop density (Al-Abbas et al., 1974; Chang et al., 2003; Osborne et al., 2002; Senay, 1998; Blackmer et al., 1996a; Flowers et al., 2001; Flowers et al., 2003a). Chang et al. (2003) noted that NIR is inversely correlated to corn yield when measurements were taken before the third leaf because soil moisture influenced the measurements. High reflectance at that time indicated low soil moisture and eventual low yields. Beyond the second leaf, NIR reflectance was positively correlated to yield. Osborne et al. (2002) noted that green, red, and NIR could predict N concentration in corn in June, but that in July N was better estimated by NIR associated with canopy biomass. Al-Abbas et al. (1974) found that NIR and middle infrared (MIR) spectra significantly varied with treatment in corn. Leaf age did not contribute to MIR reflectance variations as it did in the visible 530 and 640 nm wavebands, where pigment concentration covaried with leaf age. Maas and Dunlap (1989) reported no qualitative differences in the NIR or MIR spectra among normal, etiolated, or albino leaves; however, quantitative differences were notable at 1000 nm. This is expected, since absorption by chlorophyll is very low in NIR and MIR regions. Al-Abbas et al. (1974) associated low absorption (high reflectance) at 830, 940, and 1100 nm with high chlorophyll content. Lower absorption in NIR may protect plant pigments from denaturation (Gates et al., 1965; Al-Abbas et al., 1974). Absorptance in this range, with the same efficiency as in the visible region, would frequently over heat plants and irreversibly denature the proteins (Gates et al., 1965). Transmittance through normal leaves was significantly less than through either the etiolated or albino leaves with corresponding increase in reflectance and absorptance (Maas and Dunlap, 1989). Carlson et al. (1971) and Woolley (1971) noted that normal leaves are thicker than N deficient leaves and quantitative differences at infrared as well as visible wavelengths can be related to leaf thickness and water content.

Other nutrients besides N also can affect NIR reflectance. Al-Abbas et al. (1974) in their study of several nutrient deficiencies noted that at 830, 940, and 1100 nm, P and Ca deficient corn leaves absorb less (reflect more) than normal leaves. Marshner (1998) noted that P deficiency may result in higher chlorophyll concentration. P and Ca deficiencies affected the chlorophyll concentration to a lesser extent than the other deficiencies studied (Al-Abbas et al., 1974). Deficiency in S, Mg, K and N resulted in much higher absorptance (lower reflectance) than the normal leaf. Higher than normal absorption (lower than normal reflectance) is attributed to above normal heat content within the leaves (Al-Abbas et al., 1974). Beyond the NIR, is the middle infrared region (MIR 1350 to 2500 nm). Characteristically, with increasing N treatments, reflectance decreases in the visible where radiation is absorbed by plant pigments and in the MIR where radiation is absorbed by plant water. Reflectance increases in the NIR (Gates et al., 1965; Al-Abbas et al., 1974).

Spectral measurements are often recorded by equipment as digital counts that are proportional to the amount of reflected radiation from the target as in the case of spectroradiometers. The same is true for aerial photography where the image, a recording of reflected radiation, is digital or digitized and the digital numbers (DNs) of each pixel can be enumerated. However, raw counts are difficult to use because instrument response is typically not uniform over all wavebands, and the absolute scale is dependent on factors such as sensor, illumination angles, and canopy arch (Blackmer et al., 1996a). These inconsistancies can usually be avoided by referencing data to incident or incoming radiation acquired using a reference panel (Blackmer et al., 1996a; Bausch, 1993; Williams et al., 2001; Shanahan et al., 2001; Walburg et al., 1982; Osborne et al., 2002) or invariant object resulting in percent reflectance (Chang et al., 2003). The raw counts have also been used directly in vegetation indices (Flowers et al., 2001; Flowers et al., 2003a, 2003b). However, if vegetation indices are not calculated from percentages, the reflectance results may not be consistent when images are compared over time (U.S.

Water Conservation Laboratory, 2004). Reflectance is the hardest value to obtain, but the most valuable since it is characteristic of the surface itself and not affected by the intensity of light shining on it (U.S. Water Conservation Laboratory, 2004). Rather than use incident radiation or an invariant object, Blackmer et al. (1996a) standardized the raw counts of reflected radiation using the highest-N-rate plots within a hybrid to give values of relative reflectance where:

$$\text{Relative Reflectance} = \frac{\text{Digital Count}}{\text{Reference Digital Count}} \qquad [1]$$

Reflected radiation expressed as relative reflectance did not alter the interpretive importance of the 550 nm and 710 nm wavebands. However, comparisons to NIR wavebands resulted in inverse relationships rather than the expected positive relationship (Blackmer et al., 1996a, 1996b). Most of the single-wavelength reflectance measurements had significant hybrid effects and hybrid x N treatment effects. Blackmer et al. (1996a, 1996b) found relative reflectance able to account for differences in conditions between years, hybrids, soil fertility level, and instrumentation. Relative reflectance can be used with aerial photography, as well as radiometric measurements. When relative yield was also calculated in a similar manner, it was possible to evaluate management areas with more than one hybrid where relative reflectance explained 94% of the differences (Blackmer et al., 1996b). Use of relative reflectance with non-limiting reference plots makes it possible to use less expensive equipment by internally calibrating to a field situation (Blackmer et al., 1996a). Flowers et al. (2003a) also found that weeds, variety and soil type confounded the relationship between GS-25 tiller density (TD) in wheat and NIR digital counts. They used an approach similar to Blackmer et al. (1996a) to determine the likelihood of predicting tiller density in wheat at GS-25 and GS-30 developmental stages critical to in-season N applications. Using digital counts obtained from aerial photography, and modifying the relative reflectance model used by Blackmer et al. (1996a, 1996b); Flowers et al. (2003a) developed the following relationship where:

$$\text{Relative Reflectance} = \frac{\text{NIR} - \text{NIR}_{\text{lowest density}}}{\text{NIR}_{\text{highest density}} - \text{NIR}_{\text{lowest density}}} \quad [2]$$

Highest density and lowest density represent the NIR digital counts for the highest and lowest tiller densities at the particular location. This relationship was applied to NIR measurements within hybrid and location. Like Blackmer et al. (1996a, 1996b), when NIR digital counts alone were regressed against tiller density at each location, significant varietal and environmental differences were apparent (Flowers et al., 2001; Flowers et al., 2003a). However, when relative tiller density was regressed against relative NIR reflectance (Eq. 2), the slopes and intercepts of the equations were not significantly different. Nor was the slope and intercept of the equation resulting from the regression of data combined across all locations and hybrids significantly different from the equations of the individual locations. Flowers et al. (2001, 2003a) rearranged the linear regression equation to produce the following equation that was used to predict tiller density:

$$\text{TD}_{\text{predicted}} = \left[(\text{TD}_{\text{max}} - \text{TD}_{\text{min}})x(\text{NIR}_{\text{rel}} - .07)/1.04\right] + \text{TD}_{\text{min}} \quad [3]$$

TD means tiller density, and max and min represent the highest and lowest tiller densities at the particular location. In their 2003 study, Eq. [3] correctly recommended N applications, relative to tiller density, across hybrids and locations 85.5% of the time. The TD_{max}, TD_{min}, NIR_{max}, and NIR_{min} must be determined for each soil type or variety. Weed populations continue to be a problem and cannot be corrected with relative parameters. They have to be physically kept to a minimum. Fields with good weed control may be candidates for remote sensing while those with weeds are not (Flowers et al., 2003a).

Vegetation indices reduce multiband observations (radiometric and digital image) to a single numerical index (Wiegand et al., 1991). This use of ratios has also been shown to minimize some multiplicative effects while enhancing small increases in vegetation coverage (Epiphanio and Huete, 1994), but they are influenced by sensor calibration, sun and view angle, canopy variation, leaf optical properties, and canopy background (Yoshioka et al., 2000). One of the earliest vegetation indices was simply NIR reflectance divided by red reflectance (Jordan, 1969). This Simple Vegetation Index took advantage of the contrast between the NIR low absorption (high reflectance) and the high absorptance (low reflectance) of the red waveband by chlorophyll (Epiphanio and Huete, 1994; Shanahan et al., 2001; US Water Conservation Laboratory, 2004). Areas of dense vegetation will appear very bright in NIR and very dark in red because only about 4% of the red waveband is reflected (US Water Conservation Laboratory, 2004). A yellow leaf will appear much brighter than a healthy leaf in the red waveband where there is little chlorophyll content to absorb the light. Both the healthy and yellowed leaves will reflect light similarly in the NIR (US Water Conservation Laboratory, 2004). 8-bit digital images present brightness and darkness on a scale of gray shades between 0 for black and 255 for white. For indices that subtract red from NIR, materials with similar NIR and red brightness becomes dark. The soil, which usually reflects about the same for both red and NIR, becomes dark. If NIR is brighter than red, the ratio will be larger (i.e., brighter). With increased red absorptance, a smaller amount of red reflectance is subtracted from NIR, leaving a difference.

NDVI (Normalized Difference Vegetation Index), developed by Tucker (1979) was intended to estimate green biomass where:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{red})}{(\mathrm{NIR} + \mathrm{red})} \qquad [4]$$

The difference divided by the sum compensates for differing amounts of incoming light and is ideally suited for detecting subtle coverage differences in early crop stages or crops under stress conditions. NDVI ranges from 0.0 to 1.0 with soil producing an NDVI value of approximately 0.1 while dense vegetation gives a value of about 0.9. Aparicio et al. (2000), Epiphanio and Huete (1994), and Huete (1988) found that NDVI is highly sensitive where the leaf area index (LAI) is between 0 and 2. At LAI greater than 3, sensitivity to environmental changes diminishes (Aparicio et al., 2000; Epiphanio and Huete, 1994), because once ground coverage by vegetation is complete red absorptance saturates while NIR reflectance gradually increases with increasing canopy density. Flowers et al. (2003b) found that whole plant N at GS-30 in wheat had a relatively strong relationship with individual bands or, spectral indices, especially NDVI, where there was high biomass. NDVI produced an $r^2 = 0.69$. At low biomass, they found a poor relationship between whole plant N and spectral information because the amount of canopy coverage did not relate spectral information to the whole plant N concentration (Flowers et al., 2003b). NDVI could predict N rate 64% of the time where there was high biomass. According to the Flowers et al. (2003b) study, NDVI was still among the best estimators at all sites ($r^2 = 0.61$) when correlated to N uptake (whole plant N x biomass). The index saturated at high GS-30 biomass (high N uptake) values making differentiation by NDVI difficult, which may limit its usefulness in predicting GS-30 N uptake (Flowers et al., 2003b).

NDVI is affected by view angle, increasing as the angle moves from antisolar to forward scattering. In addition, NDVI also increases as the solar zenith angle increases, adding more depth to the canopy (Epiphanio and Huete, 1994), because there is more absorptance of red and less reflectance to subtract from NIR (U.S. Water Conservation Laboratory, 2004). Aparicio et al. (2000) found that NDVI is limited for use as a crop-area indicator. Epiphanio and Huete (1994) found NDVI to be a sensitive growth index for early crops or other sparse canopies, but it was influenced by factors other than vegetation and angle, such as soil. However, Chang et al. (2003) noted that including soil data early on provides information about drainage, organic matter, and texture, which later impacts yield (Chang et al., 2003). Bausch (1993) found that soil background color significantly altered NDVI values throughout the vegetative growth period in corn. NDVI values are greater where vegetation covers dark soils than where the soil is light in color (Chang et al., 2003). Soil type differences present a problem for remote sensing because they commonly occur within a field (Flowers et al., 2003a).

In answer to limitations surrounding NDVI, Huete (1988) introduced the "L" factor into NDVI to create the Soil Adjusted Vegetation Index where:

$$\mathrm{SAVI} = \left[\frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red} + \mathrm{L}}\right](1 + \mathrm{L}) \qquad [5]$$

"L" adjusts for the different brightnesses of the background soil. The factor "L" made SAVI less sensitive to red reflectance changes and more sensitive to NIR changes, especially for high amounts of vegetation (Epiphanio and Huete, 1994). By definition, "L" varies from 0 to 1; 1 represents low vegetation coverage and the adjustment factor diminishes as the vegetation grows denser. However, 0.5 is often used as a reasonable approximation when the amount of soil in the scene is unknown (U.S. Water

Conservaiton Laboratory, 2004). SAVI is a better estimator of LAI and biomass than NDVI at high vegetation density, and has the opposite response of NDVI with regard to view angle (Epiphanio and Huete, 1994). In contrast to NDVI, values start higher in antisolar viewing and decrease as the angle moves to forward scattering. However, SAVI is more sensitive to NIR variation caused by sensor and sun geometry. NIR has much more interaction with the canopy due to scattering and transmission compared to the red band. At high vegetation densities, SAVI is expected to be better correlated to NIR-related environmental variables, because in this range SAVI is more sensitive to NIR without saturation. This sensitivity also made SAVI more sensitive to view angle variation induced by changes in sensor and sun geometry in medium to high density alfalfa. NDVI tends to saturate at LAI greater than 3 (Aparicio el al., 2000; Epiphanio and Huete, 1994).

A year after Huete (1988) developed the SAVI, Baret et al. (1989) published modifications to it, the Transformed Soil Adjusted Vegetation Index where:

$$\mathrm{TSAVI} = \frac{a[\mathrm{NIR} - (a * \mathrm{red}) - b]}{[\mathrm{red} + (a * \mathrm{NIR}) - (a * b)]} \qquad [6]$$

where a = the slope and b = the intercept of an equation fitted through a plot of NIR vs. red reflectance data for a variety of bare soil conditions: dry, wet, smooth, and rough (Shanahan et al., 2001; Wiegand et al., 1991). Representation by only one condition, such as dry soil, would account for only a short segment of the line, skewing the slope (Wiegand et al., 1991). For this reason, Wiegand et al. (1991) took periodic soil spectral measurements throughout the season under various conditions. Using the parameters a and b, the index value becomes exactly zero for all points on the soil line (Yoshioka et al., 2000). The differences in the reflectance contributions from bare soil areas are exactly proportional to the differences in soil brightness in both the red and NIR bands. The changing rate of NIR reflectance to red reflectance is exactly the same as that of background brightness, which is the slope of the soil line, α (Yoshioka et al., 2000).

The Green Normalized Difference Vegetation Index (GNDVI), developed by Gitelson et al. (1996), is still another vegetation index, but it makes use of the green waveband in place of the red waveband:

$$\mathrm{GNDVI} = \frac{(\mathrm{NIR} - \mathrm{green})}{(\mathrm{NIR} + \mathrm{green})} \qquad [7]$$

GNDVI was correlated to corn yield more consistently throughout the season than NDVI or TSAVI. Values obtained during mid grain filling stage would have the greatest potential for estimating final grain yields over other indices (Shanahan et al., 2001). GNDVI could prove useful in producing relative yield maps that depict spatial variability in the field before harvest while there is still time to improve conditions (Shanahan et al., 2001). Blackmer et al. (1994), Schepers et al. (1992), and Schepers et al. (1996) found that the green band, together with NIR (GNDVI), is better at showing the variability in leaf chlorophyll, N content, and grain yield compared to indices using the red band (NDVI, SAVI, TSAVI). The green band where there is less absorptance provides the most sensitive assessment of N status. NDVI values have been associated with crop biomass accumulation, LAI, chlorophyll concentration in leaves, PAR absorbed by the canopy, and crop yield. However, when chlorophyll content, fractional coverage, or LAI reach moderate to high values, NDVI is apparently less sensitive to these parameters, whereas GNDVI consistently exhibited the highest correlation.

Several wavelengths, relative reflectance, and vegetation indices have been successful in estimating crop parameters such as nutrient status, crop coverage, and yield.

Success appears dependent on strict attention to spectral measurement protocol, an understanding of the spectral measurements and relationship to plant structure, and the limitations of the vegetation indices. While much of the field research has focused on field crops, greenhouse research performed by Thomas and Gausmann (1977) also included several fruit and vegetable crops: cantaloupe (*Cucumis melo* L. cv *reticulatus* Naud), cucumber (*Cucumis sativus* L.), lettuce (*Lactura sativa* L. cv *capitata* L.), and spinach (*Spinacia oleracea* L.).

Guided by the research discussed above, this chapter presents the results of correlating the field response to N treatments using conventional sampling to spectral measurements to determine whether the N requirement for quality carrot tops is manageable using remote sensing. The conventional parameters used to measure the field response to N treatments were compared to individual wavelengths, NDVI, SAVI, TSAVI and GNDVI.

Materials and Methods

Experimental Sites, Plot Design, Management Protocol, and Agronomic Sampling

Field studies were conducted at four locations during 2001 and 2002, in Montcalm County, Michigan. In both years, plots were located at the Michigan State University Montcalm Experiment Station on moderately well drained loamy sand to sandy loam soil, of the Hillsdale-Spinks map unit (Hillsdale: coarse-loamy, mixed, mesic Typic Hapludalfs, Spinks: sandy, mixed, mesic Psammentic Hapludalfs) (D.L. Mokma, personal communication, 2003). Diamond Cut and Goliath varieties were planted in both years on flat beds in early May and harvested in mid-September. Each year plots were also established on commercial carrot fields, at Sandyland Farms, on Plainfield Sand, including a loamy substratum at the 2001 site, (mixed mesic Typic Udipsamments) (D.L. Mokma, personal communication, 2003). Asgrow B1 and Prime Cut 59 varieties were planted at the 2001 site, and Sugar Snax 54 was planted at the 2002 site. These fields were planted in mid-April on raised beds and harvested in mid-August. Barley was planted between rows to protect emerging plants and killed off once the carrots were established. Four replications of each of four N-treatments (45, 90, 135, and 180 kg ha^{-1}) were arranged in a randomized complete block design at all locations. Weeds were controlled with linuron, and foliar blight was controlled with chlorothalonil. A detailed description is given in the Materials and Methods section of Chapter 1.

Reflectance and Agronomic Measurements

Plant and soil reflectance measurements were made using a MSR87, multispectral radiometer (CropScan, Rochester, MN) equipped with the standard eight narrowband interference filters centered at 460, 510, 560, 610, 660, 710, 760 and 810 nm. The MSR87 is equipped with 8 up- and 8 down-facing channels designed for near simultaneous measurements of incident irradiance and reflected radiance. This feature ensures the accuracy of percent reflectance calculations by eliminating any variability of sun angle or light conditions between the target and reference panel measurements. Flashed opal glass, a cosine diffuser, covered the incident irradiance (up-facing) sensors, while clear glass covered the reflected radiance (down-facing) sensors. The field of view (FOV) was 28°. All measurements were viewed at nadir. The standard vegetation filters of the MSR87 were evaluated for use in carrot by comparing them to measurements from an SE590 spectroradiometer (Spectrum Eng., Denver, CO). The SE590 is equipped with a silicon photodiode array measuring wavebands ranging from 365.7 to 1125.1 nm, each about 2.7 nm wide. Dual spectral measurements were taken at both 2001 field locations. Peak responses of the spectroradiometer were comparable to the waveband centers of the multispectral radiometer (Table 1). Reflectance was similar between the MSR87 and the SE590 in the visible spectra, but discrepancies were greater in the NIR spectra. Bandwidths of the MSR87 were wider in the NIR region than in the visible region, and therefore the average reflectance spanned a wider range. In addition, the spectroradiometer measurements may have contained unknown error, because

Table 1. Comparison of measurements taken August 20, 2001 by the SE590 spectroradiometer and CropScan multispectral radiometer. The canopy represented growth at 104 days after planting at the Montcalm Experiment Station and approximately 127 days after planting at Sandyland.

	MSR87		SE590		Reflectance‡	
Color	Centered	Range	Peak	Comparable† Range	MSR87	SE590
	nm				(%)	
			Montcalm Experiment Station (2001)			
Green	560.1	556 - 564	556.2	556.2 - 564.8	7.7	8.1
Red	659.2	654 - 665	673	655.2 - 664.1	2.7	3.2
NIR	813.2	797 - 829	828.6	797.5 - 828.6	47.6	64.5
			Sandyland (Deaner Rd.) (2001)			
Green	560.1	556 - 564	556.2	556.2 - 564.8	11.7	12.3
Red	659.2	654 - 665	676	655.2 - 664.1	4.1	4.3
NIR	813.2	797 - 829	813	797.5 - 828.6	65.3	79.2

† Range is based on the MSR87 that has wider bandwidths
‡ Reflectance % is the average of the range

downwheling irradiance and radiance from the canopy were measured separately. Any wisp of cloud cover between readings could have induced error. Since the MSR87 measures both irradiance and radiance simultaneously, its reflectance measurements were viewed as more accurate.

In the MSR87, incident irradiance and reflected radiance (W m^{-2}) passing through the filters is converted to electrical current by the detectors, amplified to millivolts (mV) and quantized to 8-bit radiometric resolution by the analog-to-digital converter of the Data Logger Controller (DLC). Additional software was used to apply temperature and sun angle cosine corrections to the digital output and perform percent reflectance calculations (CropScan, Inc., 1995). The viewing height was 2.55 m from the soil surface providing an effective ground resolution diameter of 1.27 m, (i.e. a 1.27 m composite measurement of plant canopy and soil reflectance).

In 2001, at the experiment station, reflectance measurements were taken weekly beginning at planting and continuing until harvest. The intensive scanning schedule was intended to track canopy development and determine a feasible future starting date when the partial canopy would be large enough that the reflectance measurements provided useable information. Measurements taken in 2002 were delayed until July 11, when the carrot canopy was partially developed, and readings per plot were increased from 2 to 4 to account for canopy variability. The Deaner Rd. (2001) and Masters Rd. (2002) fields were scanned weekly using the same protocol as at the experiment station. Table 2 describes site-specific information pertinent to reflectance measurements. The direction of scanning was determined based on minimizing shadows by plants and the operator.

A Canon Powershot G1 digital camera was mounted alongside and at the same height as the radiometer at sampling. Digital images were taken of at least one scanned site per plot for a visual record of radiometric measurements and to determine percent vegetation coverage. Ground resolution of the digital camera at a height of 2.55 m is 2.4 x 1.83 m. The images were cropped to the same ground resolution as the radiometer and reclassified to quantify pixels as soil or vegetation using Erdas Imagine 8.5.

Table 2. Reflectance measurement protocol specific to individual field locations.

	Experiment Stn† Range 1, 2001	Experiment Stn† Range 15, 2002	Deaner Rd. 2001	Masters Rd. 2002
Row orientation	East - West	East - West	North - South	East - West
Scanning Dir.	East	East	South	West
Samples per plot	2	4	2	4
Sun Angle Range	20.4° - 39.4°	21.4° - 51°	27.1° - 43°	23° - 41.3°
Viewing Plane	Principal	Principal	Orthogonal	Principal
Planting Date	May 8	May 7	Mid Apr	Mid Apr
Harvest Date	September 13	September 13	August 23	August 20
Begin Scanning	June 13	July 11	June 13	July 11
End Scanning	September 6	September 6	August 9	August 15

† Experiment Stn. refers to the Montcalm Experiment Station in Montcalm County.

Analysis of the Data

Relationships between the N treatments, petiole samples, and yield versus reflectance measurements were evaluated using regression and general linear models (SAS Inst. Inc., Release 8.2/2004). Data points of reflectance that were consistantly recorded as outliers according to SAS were eliminated. Vegetation indices were applied according to the equations set forth previously. The factor "L" in SAVI, Eq. 5, was defined as 0.50 as a reasonable approximation of vegetation cover (U.S. Water Conservation Laboratory, 2004), and in SAVISL as the soil line slope. The soil line model required by SAVISL and TSAVI was developed using regression of the NIR and red reflectance measurements of the soil. The soil line was calculated separately for each location, where possible. In 2001, spectral measurements of the soil were taken only once at the Montcalm Experiment Station. Since the Sandyland location was already established when the plots were staked, a large enough area of bare soil was no longer available. The soil line equation used for Sandyland was the same line used with Experiment Station spectra. Soils from the two locations were similar in color, organic matter content, and water holding capacity. The soil line for both the Montcalm Experiment Station and Sandyland in 2002 was derived from on-site bare soil measurements taken throughout the season. During the season conditions developed at the Experiment Station that caused the soil line slope to shift. Generally differences in soil type will alter the slope (Rondeaux et al., 1995); while wet and dry surface conditions generate the full range of the regression line (Wiegand et al., 1991). During rain events at the Montcalm Experiment Station, soils that had been disked were washed and settled by the rain resulting in exposed sand granuals and stones. The settled soils with exposed sand grains could have altered the appearance enough to change the slope of the soil line. Therefore, the 2002 soil line regression equations were calculated using weekly soil reflectance measurements taken up to peak canopy coverage.

Results and Discussion

N Status of Carrot Canopy as the Result of Soil-N Availability.

Individual Reflectance: Individual wavebands centered at 460, 510, 560, 610, 660, 710, 760, and 810 were compared to three variations of the N treatments using regression analysis to determine which bands had the strongest relationship to the N status of the carrot canopy, as a result of the soil N available. Each spectral measurement was compared to N Treatment (the total of seasonal applications) to determine if there was a point at which the canopy reflected the seasonal outcome. In addition spectral measurements were compared to Applied N (the total amount of N applied as of the date of the particular spectral measurement) and to Available N (the total amount of the residual N from the previous crop added to Applied N) to determine whether the temporal nature of spectral measurements could characterize existing field conditions. The purpose of comparing the three different variations of soil-N was to understand the nature of the predictability of reflectance measurements for use as an in-season management tool. Regression analysis showed the relationship of individual reflectance measurements to Treatment, Applied N, and Available N on any specific date was best described by a first order equation, similar to results of Flowers et al. (2003b).

In 2001, the earliest reflectance measurements were taken at the Montcalm Experiment Station on May 18, ten days after planting; plants were barely emerging (Table 3). Measurements in all wavebands were significantly correlated to Available N; depicting a spurious relationship to soil rather than plant canopy. After May 18, correlation of the reflectance measurements at 760 and 810 nm were no longer significant. Visible bands continued to correlate with Available N through July 5, but only accounted for 28 to 35% of the variation among reflectance measurements. At that time, canopy coverage averaged 19%, and reflectance depicted the plant response to N available from the previous season and the first application of 45 kg ha^{-1} N applied to all plots. The coefficient of determination was low probably because soil was an important component of the spectral measurements during early season. Table 3 also illustrates, beginning with July 12 and lasting throughout most of the remaining season, an unexpected lack of correlation of the reflectance measurements to any aspect of soil-N. Average canopy coverage was 35% on July 12, after the second urea application had been broadcasted at different treatment rates. Results from the variable plant emergence

Table 3. Linear regression coefficients of reflectance at individual wavelengths vs N; where N is treatment, applied N, or available N at the Montcalm Experiment Station, 2001, Diamond Cut variety.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
			460 nm			510 nm			560 nm		
		%	r^2								
5/18	10	0	ns	------	0.46**	ns	------	0.47**	ns	------	0.48**
6/13	36	0	ns	------	ns	ns	------	ns	ns	------	ns
6/22	45	7	ns	------	0.28*	ns	------	0.31*	ns	------	0.28*
6/28	51	11	ns	------	0.31*	ns	------	0.32*	ns	------	0.33*
7/5	58	19	ns	------	0.30*	ns	------	0.33*	ns	------	0.35*
7/12	65	35	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/20	73	64	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/26	79	85§	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/2	86	94	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/9	93	97	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/17	101	96	------	------	------	0.27*	0.27*	ns	ns	ns	ns
9/6	121	95§	------	------	------	ns	ns	ns	0.35*	0.35*	0.34*
			610 nm			660 nm			710 nm		
		%	r^2								
5/18	10	0	ns	------	0.49**	ns	------	0.49**	ns	------	0.39*
6/13	36	0	ns	------	ns	ns	------	ns	ns	------	ns
6/22	45	7	ns	------	0.29*	ns	------	0.32*	ns	------	ns
6/28	51	11	ns	------	0.34*	ns	------	0.35*	ns	------	0.33*
7/5	58	19	ns	------	0.35*	ns	------	0.35*	ns	------	0.34*
7/12	65	35	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/20	73	64	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/26	79	85§	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/2	86	94	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/9	93	97	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/17	101	96	0.47**	0.47**	0.40**	ns	ns	ns	ns	ns	ns
9/6	121	95§	0.45**	0.45**	0.44**	0.38*	0.38*	0.35*	0.37*	0.37*	0.37*
						760 nm			810 nm		
		%	r^2								
5/18	10	0				ns	------	0.48**	ns	------	0.48**
6/13	36	0				ns	------	ns	ns	------	ns
6/22	45	7				ns	------	ns	ns	------	ns
6/28	51	11				ns	------	ns	ns	------	ns
7/5	58	19				ns	------	ns	ns	------	ns
7/12	65	35				ns	ns	ns	ns	ns	ns
7/20	73	64				ns	ns	ns	ns	ns	ns
7/26	79	85§				ns	ns	ns	ns	ns	ns
8/2	86	94				ns	ns	ns	ns	ns	ns
8/9	93	97				ns	ns	ns	ns	ns	ns
8/17	101	96				ns	ns	ns	ns	ns	ns
9/6	121	95§				0.25*	0.25*	0.25*	ns	ns	ns

†trt = Treatment, app = Applied N, avail = Available N. Urea was broadcasted: June 13, July 11, and August 9. ‡DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images

*,**,*** Significance of overall F-ratio at p $\leq$0.05, 0.01, 0.001. ns = Overall F-value is not significant.

due to heavy rains in May (20.7 cm) and equipment wheel damage to some beds became apparent as the developing canopy began to dominate spectral measurements. The early conditions resulted in gaps in the rows that may have interrupted the developing correlation between N treatments and reflectance both in the visible and NIR wavebands. In addition, high residual NO_3^- from the previous crop and irrigation water, and sporadic irrigation from the adjacent field may have skewed the planned in-season N availability. Mean separation of the reflectance measurements confirmed that blocking was a significant factor throughout most of the growing season. A week after the last N application was broadcast August 9 at peak canopy coverage, correlation between Treatment, Applied N, and Available N was significant. Although, regression analysis typically resulted in low coefficient of determination, mean separation between reflectance measurements did show significant differences between treatments for reflectance measurements of wavebands centered at 610, 660, and 710 nm, and the significant differences were in order of treatment (Table 4). Results for Applied N were identical to Treatment since incremental applications were broadcast in proportions similar to the seasonal treatment increments.

The 2001 Sandyland location (Table 5), planted for "cut and peel", was seeded at approximately four times the rate used at the experiment station. The mid-April planting date and the barley cover facilitated plant establishment before the heavy rains in May, resulting in a better stand than at the Montcalm Experiment Station. Until July 5, when vegetation coverage was approximately 63%, results of the regression model reflected the N from the previous season available at the time of planting (Chapter 1, Table 3), and subsequent application of 45 kg ha^{-1} to all plots. Predictability was low much like the

Experiment Station early results. Soil and the senesced barley were important factors.

Table 4. Mean reflectance measurements as influenced by treatment or applied N at the Montcalm Experiment Station, 2001, Diamond Cut variety.

Treatment	Wavelength	August 17	September 6
Kg ha^{-1}	(nm)	----------Reflectance %----------	
45	610	5.11^{a}	5.40^{a}
90		5.04^{ab}	5.01^{ab}
135		4.97^{ab}	4.91^{b}
180		4.96^{b}	4.88^{b}
p-value		0.03	0.02
45	660	ns	3.38^{a}
90		ns	3.17^{ab}
135		ns	3.13^{ab}
180		ns	3.10^{b}
p-value			0.04
45	710	ns	10.90^{a}
90		ns	10.07^{ab}
135		ns	9.98^{ab}
180		ns	9.89^{b}
p-value			0.04

Mean values with the same letters are not significantly different at p = 0.05 based on HSD. Results for Treatment and Applied N are the same.
p-value is of the overall F-ratio. ns = Overall F-ratio is not significant.

It was too early to expect significant correlation to Treatment and Applied N since differing rates of N had not yet been applied. Reflectance in the visible part of the spectrum, at wavelength 560 nm, was the first to show significance with Available N on June 22 at 43% vegetative coverage (Table 5). On July 12, approximately six days after the first broadcast of urea at differing treatment rates, the regression model for the waveband at 560 nm was significantly correlated to Treatment, and Applied N, as well as Available N, and reflectance at 710 nm was significantly correlated to Applied N and Available N. The mean separation of reflectance measurements (Table 6) showed significant separation of treatment at 560 and 710 nm; however, predictability was less

Table 5. Linear regression coefficients of reflectance at individual wavelengths vs N; where N is treatment, applied N, or available N at Sandyland, 2001, Asgrow B1 and Prime Cut 59 varieties.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
			460 nm			510 nm			560 nm		
		%	r^2								
6/13	54	21	ns	------	ns	ns	------	ns	ns	------	ns
6/22	63	43	ns	------	ns	ns	------	ns	ns	------	0.26*
6/28	69	63	ns	------	0.37*	ns	------	0.36*	ns	------	0.34*
7/5	76	63	ns	------	ns	ns	------	ns	ns	------	ns
7/12	83	89	ns	ns	ns	ns	ns	ns	0.35*	0.40**	0.46**
7/19	90	93	ns	ns	0.26*	ns	ns	ns	0.38*	0.36*	0.28*
7/26	97	98§	ns	ns	ns	0.71***	0.75***	0.72***	0.54**	0.56***	0.54**
8/2	104	99§	ns	ns	ns	0.64***	0.68***	0.64***	0.66***	0.70***	0.66***
8/9	111	99	ns	ns	ns	0.70***	0.76***	0.75***	0.81***	0.84***	0.83***
8/17	119	99	ns	ns	ns	0.85***	0.85***	0.85***	0.90***	0.90***	0.90***
			610 nm			660 nm			710 nm		
		%	r^2								
6/13	54	21	ns	------	ns	ns	------	ns	ns	------	ns
6/22	63	43	ns	------	ns	ns	------	ns	ns	------	ns
6/28	69	63	ns	------	0.36*	ns	------	0.36*	ns	------	0.35*
7/5	76	63	ns	------	ns	ns	------	ns	ns	------	ns
7/12	83	89	ns	ns	ns	ns	ns	ns	ns	0.25*	0.31*
7/19	90	93	0.48**	0.48**	0.42**	ns	ns	ns	0.27*	0.25*	ns
7/26	97	98§	0.74***	0.78***	0.75***	0.65***	0.70***	0.68***	0.60***	0.64***	0.62***
8/2	104	99§	0.74***	0.79***	0.75***	0.64***	0.68***	0.64***	0.60***	0.65***	0.61***
8/9	111	99	0.82***	0.87***	0.86***	0.72***	0.78***	0.77***	0.77***	0.82***	0.81***
8/17	119	99	0.89***	0.89***	0.89***	0.84***	0.84***	0.84***	0.89***	0.89***	0.89***
						760 nm			810 nm		
		%	r^2								
6/13	54	21				ns	------	ns	ns	------	ns
6/22	63	43				ns	------	0.28*	ns	------	0.29*
6/28	69	63				ns	------	0.49**	ns	------	0.49**
7/5	76	63				ns	------	0.45**	ns	------	0.46**
7/12	83	89				ns	ns	ns	ns	ns	ns
7/19	90	93				0.32*	0.36*	0.42**	0.33*	0.37*	0.43**
7/26	97	98§				0.43**	0.48**	0.52**	0.44**	0.49**	0.53**
8/2	104	99§				0.30*	0.34*	0.40**	0.38*	0.42**	0.48**
8/9	111	99				ns	ns	ns	ns	ns	ns
8/17	119	99				ns	ns	ns	ns	ns	ns

†trt = treatment, app = applied N, avail = available N. Urea was broadcasted: June 13, July 6, and August 1.

‡DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*,**,*** Significance of overall F-ratio at p ≤0.05, 0.01, 0.001. ns= Overall F-ratio is not significant.

Table 6. Mean reflectance measurements as influenced by treatment or applied N at Sandyland, 2001, Asgrow B1 and Prime Cut 59 varieties.

Treatment	Wavelength	July 12	July 19	July 26	August 2	August 9	August 17
Kg ha^{-1}	(nm)	----------Reflectance %----------					
45	510	ns	ns	4.10a	4.03a	4.40a	4.27a
90		ns	ns	3.87b	3.85ab	4.01b	3.95b
135		ns	ns	3.73b	3.68b	3.72c	3.57c
180		ns	ns	3.72b	3.71b	3.78bc	3.55c
p-value				0.0001	0.0005	<0.0001	<0.0001
45	560	9.61b	ns	11.49a	11.59a	12.51a	12.74a
90		10.27ab	ns	11.11ab	11.01b	11.50b	11.86b
135		10.67a	ns	10.60b	10.58b	10.53c	10.55c
180		10.31a	ns	10.69b	10.62b	10.52c	10.27c
p-value		0.004		0.0043	0.0004	<0.0001	<0.0001
45	610	ns	6.17a	6.99a	6.69a	7.55a	7.82a
90		ns	5.98ab	6.53b	6.21b	6.74b	7.02b
135		ns	5.82ab	6.14c	5.91c	6.11c	6.18c
180		ns	5.70b	6.17c	5.92bc	6.10c	6.03c
p-value			0.013†	<0.0001	<0.0001	<0.0001	<0.0001
45	660	ns	ns	3.75a	3.36a	3.82a	3.89a
90		ns	ns	3.42b	3.13ab	3.42b	3.51b
135		ns	ns	3.26c	2.99b	3.16c	3.11c
180		ns	ns	3.26c	2.97b	3.22c	3.10c
p-value				<0.0001†	0.0012	<0.0001	<0.0001
45	710	12.45b	ns	14.68a	14.46a	16.27a	16.60a
90		12.98ab	ns	14.03ab	13.65b	14.77b	15.26b
135		13.71a	ns	13.44b	13.19b	13.62c	13.62c
180		12.99ab	ns	13.54b	13.25b	13.68c	13.37c
p-value		0.008		0.0011	0.0008	<0.0001	<0.0001
45	760	ns	56.57b	59.34b	ns	ns	ns
90		ns	62.01ab	65.92ab	ns	ns	ns
135		ns	66.92a	67.78a	ns	ns	ns
180		ns	63.52ab	67.52a	ns	ns	ns
p-value			0.020	0.0128			
45	810	ns	56.64b	59.24b	63.22b	ns	ns
90		ns	62.56ab	66.53ab	66.13ab	ns	ns
135		ns	68.11a	68.73a	67.93a	ns	ns
180		ns	64.22ab	68.37a	67.23ab	ns	ns
p-value			0.015	0.012	0.029		

† Blocking was significant July 19: 610 nm p-value = 0.052; July 26: 660 nm p-value = 0.003.
Mean values with the same letters are not significantly different at p= 0.05 based on HSD.
p-value is that generated from overall F-ratio. ns = Overall F-ratio is not significant.
Results for Treatment and Applied N are the same.

than 50%. Correlation generally improved throughout the season as the canopy developed, evidenced by the steady increase in the coefficient of determination to 0.90. Reflectance measured at 610 nm also showed significant correlation with Available N, Applied N, and Treatment as early as July 19, with increasing improvement over time. It was not until July 26, when canopy coverage averaged 98%, that reflectance at 510 and 660 nm significantly correlated to Soil-N. NIR reflectance measured at 760 and 810 nm was significantly correlated with Available N as early as June 22 and to Treatment and Applied N on July 19 at 93% average canopy coverage. Coefficient of determination was highest on July 26 at 98% coverage. Thereafter, it decreased because the NIR wavebands could not detect N differences in biomass at full canopy coverage, and healthy and yellow leaves appear the same. Mean separation of reflectance measurements indicated only two incidences of significant blocking interference between replications: July 19 at 610 nm and July 26 at 660 nm.

In 2002, reflectance measurements were delayed until July 11, based on 2001 early season low correlation results. At the Montcalm Experiment Station, the first application of N, in differing rates, was broadcast on June 8, and early season canopy development was normal. The Diamond Cut variety (Table 7) again showed unexpected lack of significant correlation between reflectance measurements in any waveband and Treatment, Applied N, or Available N until August 9. It was discovered that the irrigation nozzles produced uneven spray patterns, and within treatments the canopy height varied throughout the study. The uneven irrigation during June and July with water containing elevated NO_3^- concentrations may have contributed to the varied canopy height. The varied canopy height could have resulted in uncharacteristic and uneven

Table 7. Linear regression coefficients of reflectance at individual wavelengths vs N; where N is treatment, applied N, or available N at the Montcalm Experiment Station, 2002, Diamond Cut variety.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
			460 nm			510 nm			560 nm		
		%	r^2								
7/11	65	51§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/17	71	68	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/24	78	86	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/9	94	94	ns	ns	ns	ns	ns	ns	0.51**	0.51**	0.50**
8/15	100	98	ns	ns	ns	0.40**	0.40**	0.35*	0.75***	0.75***	0.73***
8/21	106	97	ns	ns	ns	0.34*	0.34*	0.34*	0.70***	0.70***	0.70***
8/30	115	88	ns	ns	ns	0.50**	0.50**	0.50**	0.75***	0.75***	0.76***
9/6	122	93	ns	ns	ns	0.49**	0.49**	0.51**	0.77***	0.77***	0.80***
			610 nm			660 nm			710 nm		
		%	r^2								
7/11	65	51§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/17	71	68	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/24	78	86	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/9	94	94	ns	ns	ns	ns	ns	ns	0.40**	0.40**	0.40**
8/15	100	98	0.61***	0.61***	0.61***	0.27*	0.27*	0.26*	0.48**	0.48**	0.52**
8/21	106	97	0.48**	0.48**	0.51**	0.23	0.23	0.25*	0.62***	0.62***	0.67***
8/30	115	88	0.64***	0.64***	0.68***	0.38**	0.38**	0.40**	0.70***	0.70***	0.77***
9/6	122	93	0.63***	0.63***	0.68***	0.38*	0.38*	0.42**	0.70***	0.70***	0.70***
						760 nm			810 nm		
		%	r^2								
7/11	65	51§				ns	ns	ns	ns	ns	ns
7/17	71	68				ns	ns	ns	ns	ns	ns
7/24	78	86				ns	ns	ns	ns	ns	ns
8/1	86	96				ns	ns	ns	ns	ns	ns
8/9	94	94				ns	ns	ns	ns	ns	ns
8/15	100	98				ns	ns	ns	ns	ns	ns
8/21	106	97				ns	ns	ns	ns	ns	ns
8/30	115	88				ns	ns	ns	ns	ns	ns
9/6	122	93				ns	ns	ns	ns	ns	ns

† trt = treatment, app = applied N, avail = available N. Urea was broadcasted on June 8, July 29, and August 24.

‡ DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at p $\leq$0.05, 0.01, 0.001. ns = Overall F-ratio is not significant.

shadowing, measured as part of the reflectance that resulted in the lack of significant correlation. On August 9, when canopy coverage averaged 94%, it was the visible bands centered at 560 and 710 nm that first became significantly correlated to Treatment, Applied N, and Available N. The second application of N at differing rates was 11 days old and rain as of July 21(Table 2, Ch. 1) had eliminated the need for irrigation with NO_3^- high water. On August 15, at peak canopy coverage averaging 98%, correlation between the visible bands at 510, 610 and 660 nm and Treatment, Applied N and Available N was first significant. Correlation remained significant in the visible bands for the remainder of the season. NIR wavebands centered at 760 and 810 nm were never significantly correlated to soil-N. It may have resulted from the uneven canopy height that was further complicated by early senescence from late season development of Aster Yellows and Alternaria leaf blight. Correlation of spectral measurements to N treatments was best described by reflectance measured in the visible bands at 560 and 710 nm with r^2 values ranging from 0.70 to 0.80. Mean separation of reflectance measurements (Table 8) indicated that wavebands at 560 and 710 nm had the greatest separation between treatments. Further, both the regression model and the mean separation of reflectance measurements indicated that reflectance at 660 nm, where chlorophyll strongly absorbs irradiance, was not a good indicator of differences in plant response to soil-N (r^2 values ranged from 0.27 to 0.42). Generally, where the regression model resulted in significant correlation of less than 40%, the difference between treatments exhibited by the mean separation of reflectance measurements was insignificant.

The Goliath variety, also planted at the experiment station and subject to the same water regime, exhibited the same irregular canopy height. In addition, in early August the plants were diagnosed with bacterial blight and Cercospora leaf spot which resulted in

Table 8. Mean reflectance measurements as influenced by treatment or applied N at Montcalm Experiment Station, 2002, Diamond Cut variety.

Treatment	Wavelength	August 9	August 15	August 21	August 30	September 9
Kg ha^{-1}	(nm)			Reflectance %		
45	510	ns	2.46a	ns	2.58a	2.64a
90		ns	2.26ab	ns	2.40ab	2.45ab
135		ns	2.23ab	ns	2.36b	2.39b
180		ns	2.19b	ns	2.32b	2.35b
p-value			0.04		0.01	0.018
45	560	5.98a	5.62a	5.71a	5.56a	5.54a
90		5.81ab	5.30b	5.42b	5.25b	5.20b
135		5.76b	5.18bc	5.35b	5.16bc	5.09bc
180		5.72b	5.00c	5.26b	5.01c	4.91c
p-value		0.014	0.0003	0.0002	<0.0001†	<0.0001†
45	610	ns	3.95a	4.20a	4.22a	4.34a
90		ns	3.72ab	3.92ab	3.93b	4.01ab
135		ns	3.60b	3.83b	3.83b	3.90b
180		ns	3.48b	3.80b	3.74b	3.79b
p-value			0.006	0.015	0.0017	0.003
45	660	ns	ns	ns	ns	ns
90		ns	ns	ns	ns	ns
135		ns	ns	ns	ns	ns
180		ns	ns	ns	ns	ns
45	710	8.96a	8.87a	9.06a	8.88a	9.03a
90		8.69ab	8.45ab	8.65ab	8.42b	8.45b
135		8.67ab	8.28ab	8.55b	8.29b	8.30bc
180		8.54b	7.86b	8.38b	8.04c	8.07c
p-value		0.053	0.009†	0.003	<0.0001†	<0.0001†
45	760	ns	ns	ns	ns	ns
90		ns	ns	ns	ns	ns
135		ns	ns	ns	ns	ns
180		ns	ns	ns	ns	ns
45	810	ns	ns	ns	ns	ns
90		ns	ns	ns	ns	ns
135		ns	ns	ns	ns	ns
180		ns	ns	ns	ns	ns

† Blocking was significant August 15: 710 nm p-value = 0.04; August 30: 560 nm p-value = 0.03, 710 nm p-value = 0.004; September 6: 560 nm p-value = 0.03, 710 nm p-value = 0.02.
Mean values with the same letters are not significantly different at p= 0.05 based on HSD.
p-value is that generated from overall F-ratio. ns = Overall F-ratio is not significant.
Results for Treatment and Applied N are the same.

considerable damage to the petioles and leaves. Table 9 illustrates the limited significance, in the visible wavebands centered at 560, 610, 660, and 710 nm, and only

Table 9. Linear regression coefficients of reflectance at individual wavelengths vs N; where N is treatment, applied N, or available N at the Montcalm Experiment Station, 2002, Goliath variety.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
			460 nm			510 nm			560 nm		
		%	r^2								
7/11	65	46§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/17	71	66	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/24	78	80	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/9	94	93	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/15	100	96	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/21	106	94	ns	ns	ns	ns	ns	ns	0.38^{**}	0.38^{**}	ns
8/30	115	87	ns	ns	ns	ns	ns	ns	0.46^{**}	0.46^{**}	ns
9/6	122	90	ns	ns	ns	ns	ns	ns	ns	ns	ns
			610 nm			660 nm			710 nm		
		%	r^2								
7/11	65	46§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/17	71	66	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/24	78	80	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/9	94	93	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/15	100	96	ns	ns	ns	ns	ns	ns	0.27^{*}	0.27^{*}	ns
8/21	106	94	0.34^{*}	0.34^{*}	ns	ns	ns	ns	0.47^{**}	0.47^{**}	ns
8/30	115	87	0.55^{***}	0.55^{***}	ns	0.32^{*}	0.32^{*}	ns	0.51^{**}	0.51^{**}	ns
9/6	122	90	ns	ns	ns	ns	ns	ns	ns	ns	ns
						760 nm			810 nm		
		%	r^2								
7/11	65	46§				ns	ns	ns	ns	ns	ns
7/17	71	66				ns	ns	ns	ns	ns	ns
7/24	78	80				ns	ns	ns	ns	ns	ns
8/1	86	96				ns	ns	ns	ns	ns	ns
8/9	94	93				ns	ns	ns	ns	ns	ns
8/15	100	96				ns	ns	ns	ns	ns	ns
8/21	106	94				ns	ns	ns	ns	ns	ns
8/30	115	87				ns	ns	ns	ns	ns	ns
9/6	122	90				ns	ns	ns	ns	ns	ns

†trt = treatment, app = applied N, avail = available N. Urea was broadcasted on June 8, July 29, and August 24. ‡ DAP = Days after planting

§ Calculated approximation using NDVI rather than the approximation developed from images.

*,**,*** Significance of overall F-values at p $\leq$0.05, 0.01, 0.001. ns = Overall F-ratio is not significant.

significantly correlated to Treatment and Applied N. Reflectance at 710 nm was significantly correlated on August 15, August 21, and August 30. Reflectance at 560 and 610 nm was significantly correlated on August 21 and August 30 and at 660 nm only on August 30. Even though correlation was significant on the indicated dates in the visible wavebands, the predictability was marginal, possibly due to the now diminished canopy where soil reflectance once again was a significant part of the signal. The mean separation of reflectance measurements (Table 10) indicated that significant treatment differences could be detected only where the regression model could explain 40% of reflectance variability. While increased use of fungicide promoted recovery and new growth toward season end, the canopy never fully recovered. Structure and morphology (Al-Abbas et al., 1974) of the canopy were affected, resulting in the irregular canopy coverage as evidenced by the lack of correlation in the regression model and the unordered separation of treatments (Table 10).

In 2002 the Sandyland location (Table 11), again, was planted at a high population rate for the "cut and peel" market. The seeding rate was almost double that at the Experiment Station and the canopy was visibly denser. The mean separation of reflectance measurements (Table 12) indicated blocking was not a significant factor any time during the season. Regression analysis (Table 11) resulted in significant correlation first exhibited on July 17, when canopy coverage averaged 92%, and the first broadcast of urea, at differing rates, was about two weeks old. Visible wavebands centered at 610 and 710 nm, and NIR wavebands centered at 760 and 810 nm, were significantly correlated with Treatment, Applied N, and Available N. In 2001, the visible band at 560 nm showed significance a week earlier at 89% coverage. As of July 24, visible

Table 10. Mean reflectance measurements as influenced by treatment or applied N at the Montcalm Experiment Station, 2002, Goliath variety.

Treatment	Wavelength	August 9	August 15	August 21	August 30	September 6
Kg ha^{-1}	(nm)	Reflectance %				
45	510	ns	ns	ns	ns	ns
90		ns	ns	ns	ns	ns
135		ns	ns	ns	ns	ns
180		ns	ns	ns	ns	ns
45	560	ns	ns	4.81a	4.70a	ns
90		ns	ns	4.59ab	4.41ab	ns
135		ns	ns	4.62ab	4.47ab	ns
180		ns	ns	4.48b	4.29b	ns
p-value				0.051	0.011	
45	610	ns	ns	ns	3.57a	ns
90		ns	ns	ns	3.43ab	ns
135		ns	ns	ns	3.36ab	ns
180		ns	ns	ns	3.23b	ns
p-value					0.017	
45	660	ns	ns	ns	ns	ns
90		ns	ns	ns	ns	ns
135		ns	ns	ns	ns	ns
180		ns	ns	ns	ns	ns
45	710	ns	ns	7.83a	7.63a	ns
90		ns	ns	7.63ab	7.24ab	ns
135		ns	ns	7.50ab	7.21ab	ns
180		ns	ns	7.30b	6.96b	ns
p-value				0.046	0.015	
45	760	37.18ab	ns	ns	31.10ab	ns
90		33.81b	ns	ns	27.19b	ns
135		39.14a	ns	ns	32.38a	ns
180		37.02ab	ns	ns	29.71ab	ns
p-value		0.044			0.017†	
45	810	38.86ab	ns	ns	32.96ab	ns
90		35.56b	ns	ns	29.05b	ns
135		40.99a	ns	ns	34.52a	ns
180		38.84ab	ns	ns	31.73ab	ns
p-value		0.045			0.016†	

† Blocking was significant August 30: 760 nm p-value = 0.017, 810 nm p-value = 0.015.
Mean values with the same letters are not significantly different at p= 0.05 based on HSD.
p-value is that generated from overall F-ratio. ns = Overall F-ratio is not significant.
Results for Treatment and Applied N are the same.

Table 11. Linear regression coefficients of reflectance at individual wavelengths vs N; where N is treatment, applied N, or available N at Sandyland, 2002, Sugar Snax variety.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
			460 nm			510 nm			560 nm		
		%	r^2								
7/11	82	91§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/17	88	92§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/24	95	92	0.62***	0.62***	0.64***	0.76***	0.76***	0.78***	0.72***	0.72***	0.70***
8/1	103	97	0.51**	0.51**	0.49**	0.54**	0.54**	0.54**	0.34*	0.34*	0.33*
8/9	111	96	0.44**	0.44**	0.43**	0.47**	0.47**	0.47**	0.39*	0.39*	0.38*
8/15	117	99	0.67***	0.67***	0.66***	0.60***	0.60***	0.59***	0.40**	0.40**	0.40**
			610 nm			660 nm			710 nm		
		%	r^2								
7/11	82	91§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/17	88	92§	0.30*	0.30*	0.30*	ns	ns	ns	0.34*	0.34*	0.34*
7/24	95	92	0.81***	0.81***	0.82***	0.78***	0.78***	0.80***	0.77***	0.78***	0.78***
8/1	103	97	0.54**	0.54**	0.54**	0.61***	0.61***	0.61***	0.46**	0.46**	0.46**
8/9	111	96	0.47*	0.47*	0.47*	0.58***	0.58***	0.58***	0.31*	0.31*	0.30*
8/15	117	99	0.49**	0.49**	0.48**	0.62***	0.62***	0.62***	0.37*	0.37*	0.36*
						760 nm			810 nm		
		%	r^2								
7/11	82	91§				ns	ns	ns	ns	ns	ns
7/17	88	92§				0.43**	0.43**	0.42**	0.45**	0.45**	0.45**
7/24	95	92				0.67***	0.66***	0.70***	0.67***	0.67***	0.70***
8/1	103	97				0.54**	0.54**	0.57**	0.64***	0.64***	0.67***
8/9	111	96				0.29*	0.29*	0.33*	0.41**	0.41**	0.46**
8/15	117	99				0.24*	0.24*	0.25*	0.32*	0.32*	0.33*

† trt = treatment, app = applied N, avail = available N. Urea was broadcasted on July 3 and July 29.
‡ DAP = Days after planting
§ Calculated approximation using NDVI rather than approximation developed from images
$^{*, **, ***}$ Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$. ns = Overall F-ratio is not significant.

wavebands centered at 460, 510, 560, and 660 nm were first significantly correlated with all three variations of soil-N. In fact, the coefficient of determination peaked across wavebands on July 24, unlike Sandyland in 2001 where r^2 steadily increased, for the visible wavebands, throughout the season as the canopy developed. Reflectance measurements in 2002 appeared to indicate that the canopy was less responsive to N applications compared to 2001. Results shown in Table 12 confirmed the condition,

Table 12. Mean reflectance measurements as influenced by treatment or applied N at Sandyland, 2002, Sugar Snax variety.

Treatment	Wavelength	July 17	July 24	August 1	August 9	August 15
Kg ha^{-1}	(nm)	----------------------------	----------	Reflectance %	----------	----------------------------
45	510	ns	3.21a	3.13a	2.98a	3.09a
90		ns	2.77b	2.92ab	2.86ab	2.97a
135		ns	2.66b	2.94ab	2.93a	2.97a
180		ns	2.54b	2.70b	2.67b	2.74b
p-value			0.0004	0.007	0.004	0.002
45	560	6.24a	6.96a	ns	7.07ab	7.19a
90		5.88b	6.43b	ns	6.97ab	7.01ab
135		6.12ab	6.39b	ns	7.11a	7.08ab
180		5.97ab	6.20b	ns	6.60b	6.59b
p-value		0.025	<0.0001		0.031	0.019
45	610	4.52a	5.34a	5.00a	4.96a	4.97a
90		4.06b	4.60b	4.72ab	4.73ab	4.71ab
135		4.17ab	4.35b	4.72ab	4.84a	4.79ab
180		4.10b	4.14b	4.29b	4.39b	4.35b
p-value		0.010	0.0003	0.008	0.004	0.007
45	660	ns	3.72a	3.09a	2.92a	2.82a
90		ns	2.94ab	2.71ab	2.69ab	2.63a
135		ns	2.59b	2.63b	2.72ab	2.62a
180		ns	2.42b	2.38b	2.45b	2.36b
p-value			0.002	0.004	0.003	0.002
45	710	9.71a	10.96a	10.75a	ns	10.38a
90		9.01b	9.91b	10.49ab	ns	10.05ab
135		9.31b	9.67b	10.60a	ns	10.25a
180		9.05b	9.33b	9.79b	ns	9.44b
p-value		0.0006	<0.0001	0.014		0.016
45	760	39.44a	43.13b	43.96b	ns	ns
90		41.65ab	45.05ab	46.52ab	ns	ns
135		46.00a	49.30a	49.36a	ns	ns
180		45.12ab	50.04a	49.28a	ns	ns
p-value		0.027	0.004	0.017		
45	810	39.58b	43.77c	44.74b	ns	ns
90		41.89ab	45.89bc	47.43ab	ns	ns
135		46.58a	50.54ab	50.81a	ns	ns
180		45.64ab	51.33a	50.96a	ns	ns
p-value		0.019	0.003	0.006		

Mean values with the same letters are not significantly different at p= 0.05 based on HSD.
p-value is that generated from overall F-ratio. ns = Overall F-ratio is not significant.
Results for Treatment and Applied N are the same.

where separation of treatments was less significant and not in order. In both years the last two applications were 26 days apart. The 2002 field (Table 11) had a 2 to 6% slope and frequent irrigation may have resulted in some drainage away from the plots resulting in runoff of broadcasted N. Instead of the coefficient of determination continuing to increase until season end, it decreased as if soil-N was "used up" and the canopy stressed across all treatments before the last application on July 29, as evidenced by the drop in correlation to spectral measurements. Approximately two weeks following the final application, r^2 in the visible bands increased showing the effects of the N applied on July 29. Likewise, the mean separation of reflectance measurements (Table 12) indicated significant and orderly separation of treatments. Correlation of NIR reflectance at 760 and 810 nm continued to decrease in significance at full canopy coverage similar to 2001.

Overall canopy condition was better at Sandyland during the two-year study than at the Experiment Station. Seeding rate affected density of the canopies and disease reduced the plant vigor at the Experiment Station. Canopy condition affected the ability of NIR wavebands to correlate with soil-N when variables other than N treatments reduced plant N uptake or when full coverage eliminated the use of biomass as a means of evaluating treatments. There was little correlation of reflectance at 760 and 810 nm to soil-N at the Experiment Station while at Sandyland correlation was significant until full canopy coverage. NIR is unable to distinguish between coloring due to chlorophyll concentration (U.S. Water Conservation Laboratory, 2004); and at full canopy coverage biomass was no longer variable. However, the visible wavebands, even with blight at the experiment station, were able to provide some predictability about the plant response to soil-N. The visible bands centered at 560 and 710 nm were the earliest to correlate with soil-N and generally remained significant throughout the season explaining as much as 89-90% of the difference between treatments. The consistent results in the 560 and 710 nm wavebands at the various locations, and in both years, are in agreement with Thomas and Gausman (1977), Blackmer et al. (1994), Blackmer et al. (1996a), and Masoni et al. (1996) who found wavebands centered at 550 and 710 nm better for detecting N deficiency than other wavebands. At 550nm there was relatively little absorption by plants; therefore, a greater percentage of the irradiance was reflected providing the most sensitive assessment of N which depicted a larger separation between treatments. In addition, bands centered at 510 and 610 were also significantly correlated, although significance generally lagged by one to two weeks. The bluer green at 510 nm and the orange-red at 610 nm exhibited significance equal to or surpassing the wavelengths at 560 and 710 nm on certain dates, and may prove to be important to carrot. Plots of the individual wavebands over time revealed a curvilinear relationship. However, the prevailing conditions encountered over the season at most locations made statistical analysis difficult.

Where soil-N was significantly correlated to canopy reflectance during the early season, the correlation was generally low or sporadic because soil was such a dominant feature of target radiation. This was true across all wavebands. As split N applications in differing rates were applied, and the canopy developed, soil-N showed significant correlation within about two weeks of application (Tables 5, 7, 11) and remained constant or decreased in varying degrees of significance depending on waveband as the N application was "used-up" in about 25 days. Regression analysis indicated Applied N, defined as the total amount of N applied to date, performed slightly better in nearly all wavebands than Treatment and Available N at Sandyland 2001 (Table 5), but did not show the same distinction at other locations. Reflectance was compared to Treatment to determine if there was a point in canopy development that seasonal outcome could be predicted. Predictability was best at 560 and 710 nm at approximately 89 to 94% vegetative cover, 93 to 94 days after planting and generally after the second application. Ninety-three to 94 days after planting was at least 35 days before harvest (Chapter 1, Table 8). That is enough time to fertilize, realize results, and not accumulate excess N before harvest. Only reflectance at 460 nm failed to correlate with soil-N at most locations. Correlation of the NIR wavebands to soil-N depended on the condition of the canopy more than the visible bands. The results varied from location to location.

Selected Indices: Many factors affect reflectance measurements such as sun angle, time of day, variety, and wetness of soil surface. A number of indices have been developed to address some of these factors. Treatment, Applied N, and Available N were compared to four indices: NDVI, SAVI, TSAVI, and GNDVI chosen because they have returned a measure of success in other studies. SAVISL, is a variation of SAVI where L = soil line slope.

Table 13 shows that at the Experiment Station, in 2001 the indices followed the same trend in correlation as the individual reflectance measurements in Table 3. Indices significantly correlated to Available N from the first measurement date through July 5. The response was similar among indices, but unlike the individual wavebands, the coefficient of determination decreased approaching July 5. The decreasing response may be influenced by the lack of correlation of the reflectance at 810 nm, one of the terms of the indices equations. Thereafter, the indices showed less correlation with soil N than the individual reflectance measurements. It should be noted, that on June 13, while the components of the indices (560, 660, 810 nm) were not significant all the indices were significantly correlated to Treatment, Applied N and Available N. Again on August 17,

Table 13. Linear regression coefficients of selected indices vs N; where N is treatment, applied N, or available N at the Montcalm Experiment Station, 2001, Diamond Cut variety.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
				NDVI			SAVISL			SAVI	
		%					r^2				
5/18	10	0	ns	--------	0.45^{**}	ns	--------	0.45^{**}	ns	--------	0.45^{**}
6/13	36	0	ns	--------	0.29^{*}	ns	--------	0.29^{*}	ns	--------	0.29^{*}
6/22	45	7	ns	--------	0.37^{**}	ns	--------	0.37^{**}	ns	--------	0.37^{*}
6/28	51	11	ns	--------	0.31^{*}	ns	--------	0.31^{*}	ns	--------	0.31^{*}
7/5	58	19	ns	--------	0.29^{*}	ns	--------	0.29^{*}	ns	--------	0.29^{*}
7/12	65	35	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/20	73	64	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/26	79	85§	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/2	86	94	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/9	93	97	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/17	101	96	ns	ns	ns	ns	ns	ns	ns	ns	ns
9/6	121	95	ns	ns	ns	ns	ns	ns	ns	ns	ns
							TSAVI			GNDVI	
		%					r^2				
5/18	10	0				ns	--------	ns	ns	--------	0.41^{**}
6/13	36	0				ns	--------	0.34^{*}	ns	--------	0.29^{*}
6/22	45	7				ns	--------	0.33^{*}	ns	--------	0.33^{*}
6/28	51	11				ns	--------	0.30^{*}	ns	--------	0.31^{*}
7/5	58	19				ns	--------	0.28^{*}	ns	--------	0.29^{*}
7/12	65	35				ns	ns	ns	ns	ns	ns
7/20	73	64				ns	ns	ns	ns	ns	ns
7/26	79	85§				ns	ns	ns	ns	ns	ns
8/2	86	94				ns	ns	ns	ns	ns	ns
8/9	93	97				ns	ns	ns	ns	ns	ns
8/17	101	96				ns	ns	ns	0.31^{*}	0.31^{*}	0.28^{*}
9/6	121	95				ns	ns	ns	ns	ns	ns

† trt = treatment, app = applied N, avail = available N

‡ DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images

*, **, *** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$.

the situation was similar with GNDVI. The mean separation of index values indicated the indices at this location (not shown) could not distinguish between treatments while individual reflectance at 610, 660, and 710 could distinguish between treatments 1 and 4 (Table 4).

Similar to the individual wavebands, correlation of indices to soil-N was better at Sandyland (Table 14) than at the Experiment Station. GNDVI was the first index to significantly correlate with Available N on June 22 similar to reflectance at 560 and 810 nm. On June 28 and July 5 NDVI, SAVISL, SAVI, and TSAVI were significantly correlated to Available N while the associated reflectance measurement at 660 nm was only significant on June 28 and the NIR reflectance at 810 nm was significant on both dates; demonstrating the sensitivity of the indices to NIR (Epiphanio nad Huete, 1994) at low coverage. In contrast, on July 12, when NIR reflectance measurements were not significantly correlated to N, neither were the indices. Similar to individual reflectance measurements, all five indices were significantly correlated to Treatment, Applied N, and Available N from July 19 to season end. By August 9 the indices based on red reflectance, NDVI, SAVI, SAVISL and TSAVI, exhibited predictability equal to GNDVI in estimating N status with the coefficient of determination at 0.93 to 0.96 across all indices. NDVI and SAVI were expected to saturate at full canopy coverage, but a comparison between Table 5 and Table 14 indicates that not only did they not saturate, but the predictability of N status represented as Treatment, Applied N, or Available N, was better explained by the indices enhancing the information provided by reflectance measurements (Yoshioka et al., 2000). The indices that corrected for soil background "noise", SAVI, SAVISL, and TSAVI by rendering red less sensitive and NIR more sensitive to canopy coverage did not perform better than NDVI or GNDVI. The mean separation of index values (Table 15) indicated that all five indices differentiated between at least two treatments. GNDVI detected the difference between three treatments as early as August 2, approximately 104 days after planting.

Table 14. Linear regression coefficients of selected indices vs N; where Index = mN + b through 7/26 and N is treatment, applied N, or available N at Sandyland, 2001, Asgrow B1 and Prime Cut 59 varieties. Beginning 8/2 Index = mN + mN^2 + b.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
				NDVI			SAVISL			SAVI	
		%					r^2				
6/13	54	21	ns	--------	ns	ns	--------	ns	ns	--------	ns
6/22	63	43	ns	--------	ns	ns	--------	ns	ns	--------	ns
6/28	69	63	ns	--------	0.38^{**}	ns	--------	0.38^{**}	ns	--------	0.38^{**}
7/5	76	63	ns	--------	0.26^{*}	ns	--------	0.26^{*}	ns	--------	0.26^{*}
7/12	83	89	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/19	90	93	0.30^{*}	0.33^{*}	0.36^{**}	0.32^{*}	0.35^{*}	0.38^{*}	0.31^{*}	0.34^{*}	0.37^{*}
7/26	97	98§	0.62^{***}	0.68^{***}	0.70^{***}	0.61^{***}	0.68^{***}	0.70^{***}	0.61^{***}	0.68^{***}	0.70^{***}
8/2	104	99§	0.82^{***}	0.81^{***}	0.82^{***}	0.82^{***}	0.81^{***}	0.82^{***}	0.82^{***}	0.81^{***}	0.82^{***}
8/9	111	99	0.96^{***}	0.95^{***}	0.94^{***}	0.95^{***}	0.94^{***}	0.93^{***}	0.96^{***}	0.95^{***}	0.93^{***}
8/17	119	99	0.96^{***}	0.96^{***}	0.95^{***}	0.95^{***}	0.95^{***}	0.95^{***}	0.95^{***}	0.95^{***}	0.95^{***}
							TSAVI			GNDVI	
		%					r^2				
6/13	54	21				ns	--------	ns	ns	--------	ns
6/22	63	43				ns	--------	ns	ns	--------	0.39^{**}
6/28	69	63				ns	--------	0.38^{**}	ns	--------	0.31^{*}
7/5	76	63				ns	--------	0.26^{*}	ns	--------	0.31^{*}
7/12	83	89				ns	ns	ns	ns	ns	ns
7/19	90	93				0.31^{*}	0.34^{*}	0.37^{*}	0.52^{**}	0.56^{***}	0.60^{***}
7/26	97	98§				0.61^{***}	0.68^{***}	0.70^{***}	0.67^{***}	0.74^{***}	0.76^{***}
8/2	104	99§				0.82^{***}	0.81^{***}	0.82^{***}	0.91^{***}	0.89^{***}	0.91^{***}
8/9	111	99				0.96^{***}	0.95^{***}	0.94^{***}	0.96^{***}	0.95^{***}	0.95^{***}
8/17	119	99				0.95^{***}	0.95^{***}	0.95^{***}	0.96^{***}	0.96^{***}	0.96^{***}

† trt = treatment, app = applied N, avail = available N
‡ DAP = Days after planting
§ Calculated approximation using NDVI rather than approximation developed from images
*, **, *** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$.

In 2002, at the Montcalm Experiment Station (Table 16), the indices were not well correlated with soil-N. All five indices studied include the waveband centered at

810 nm that was never significant at this location anytime during the season. The equations for NDVI, SAVI, SAVISL and TSAVI that include reflectance at 660 nm; even though significantly correlated to soil-N, explained at most 42% of the N differences and were apparently not significant enough to overcome the insignificance of the NIR.

Table 15. Mean reflectance measurements as influenced by treatment or applied N at Sandyland, 2001, Asgrow B1 and Prime Cut 59 varieties.

Treatment	Index	July19	July 26	August 2	August 9	August 17
Kg ha^{-1}	(nm)	Index Value				
45	NDVI	0.88b	0.88b	0.90b	0.89c	0.89c
90		0.89ab	0.90a	0.91a	0.90b	0.90b
135		0.91a	0.91a	0.92a	0.91a	0.91a
180		0.90a	0.91a	0.91a	0.91a	0.91a
p-value		0.004†	<0.0001†	<0.0001	<0.0001	<0.0001
45	SAVISL	1.79b	1.77b	1.81b	1.79c	1.79c
90		1.81ab	1.82a	1.84a	1.82b	1.82b
135		1.84a	1.84a	1.85a	1.83a	1.83a
180		1.82a	1.84a	1.85a	1.83a	1.84a
p-value		0.005†	0.0002	0.0001	<0.0001	<0.0001
45	SAVI	1.32b	1.31b	1.34b	1.32c	1.32c
90		1.34ab	1.34a	1.35a	1.34b	1.34b
135		1.35a	1.35a	1.36a	1.35a	1.35a
180		1.34a	1.35a	1.36a	1.35a	1.36a
p-value		0.004†	<0.0001†	<0.0001	<0.0001	<0.0001
45	TSAVI	0.88b	0.87b	0.89b	0.88c	0.88c
90		0.89ab	0.89a	0.90a	0.90b	0.89b
135		0.90a	0.90a	0.91a	0.90a	0.90a
180		0.90a	0.90a	0.91a	0.90a	0.90a
p-value		0.004†	0.0002	<0.0001	<0.0001	<0.0001
45	GNDVI	0.77b	0.76b	0.77c	0.76c	0.76c
90		0.79ab	0.79a	0.80b	0.79b	0.78b
135		0.81a	0.81a	0.81a	0.80a	0.80a
180		0.80a	0.80a	0.81a	0.80a	0.81a
p-value		0.0025	<0.0001	<0.0001	<0.0001	<0.0001

† Blocking was significant July 19: NDVI p-value = 0.006, SAVISL p-value = 0.01, SAVI p-value = 0.008, TSAVI p-value = 0.008; July 26: NDVI p-value = 0.04, SAVI p-value = 0.05.
Mean values with the same letters are not significantly different at p = 0.05 based on HSD.
p-value is that generated from overall F-ratio.
Results for Treatment and Applied N are the same.

However, the waveband centered at 560 nm (Table 7), as of August 15, could explain as much as 75% of N differences which may have been enough to dominate the insignificance of 810 nm. GNDVI was the only index to make a significant contribution,

Table 16. Linear regression coefficients of selected indices vs N; where N is treatment, applied N, or available N at the Montcalm Experiment Station 2002, Diamond Cut variety.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail
			All other indices			GNDVI		
		%	-------------------------- r^2	--------------------------				
7/11	65	51§	ns	ns	ns	ns	ns	ns
7/17	71	68	ns	ns	ns	ns	ns	ns
7/24	78	86	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns
8/9	94	94	ns	ns	ns	ns	ns	ns
8/15	100	98	ns	ns	ns	0.30*	0.30*	0.29*
8/21	106	97	ns	ns	ns	0.51**	0.51**	0.52**
8/30	115	88	ns	ns	ns	0.46**	0.46**	0.49**
9/6	122	93	ns	ns	ns	0.39**	0.39**	0.44**

† trt = treatment, app = applied N, avail = available N

‡ DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images

*,**,*** Significance of overall F-values at p ≤0.05, 0.01, 0.001.

Table 17. Mean reflectance measurements as influenced by treatment or applied N at the Montcalm Experiment Station, 2002, Diamond Cut variety.

Treatment	Index	August 21	August 30	September 6
Kg ha^{-1}	(nm)	-----------------	Index Value	---------------
45	GNDVI	0.81b	0.78b	0.77b
90		0.82ab	0.79ab	0.78ab
135		0.82a	0.81a	0.79a
180		0.82ab	0.80a	0.79ab
p-value		0.03	0.01	0.03

Mean values with the same letters are not significantly different at p = 0.05 based on HSD. p-value is that generated from overall F-ratio.
Results for Treatment and Applied are the same.

and explained nearly 50% of soil N differences. Mean separation of index values, prepared for GNDVI only (Table 17), showed differences between treatments 1 and 3. None of the indices calculated from reflectance measurements of the Goliath canopy were significant. Canopy health at this location greatly affected the use of indices.

At the 2002 Sandyland location (Table 18) SAVISL and GNDVI showed significant correlation to soil-N even before the visible wavebands. GNDVI at 92% of canopy coverage explained as much as 53% of the differences in N on July 17. While the correlation of individual wavebands to soil-N seemed to peak on July 24 (Table 11), the indices peaked the following week, but did not attain the same level of predictability as the individual reflectance (Table 11) where reflectance at 560 nm explained 72%, and

Table 18. Linear regression coefficients of selected indices vs N; where N is treatment, applied N, or available N at Sandyland, 2002, Sugar Snax variety.

Scan Date	DAP‡	Ave Veg Cov	trt†	app†	avail†	trt	app	avail	trt	app	avail
			NDVI			SAVISL			SAVI		
		%	r^2								
7/11	82	91§	ns	ns	ns	ns	ns	ns	ns	ns	ns
7/17	88	92§	ns	ns	ns	0.27^{*}	0.27^{*}	0.28^{*}	ns	ns	0.27^{*}
7/24	95	92	0.30^{*}	0.30^{*}	0.30^{*}	0.31^{*}	0.32^{*}	0.31^{*}	0.31^{*}	0.31^{*}	0.31^{*}
8/1	103	97	0.62^{***}	0.62^{***}	0.63^{***}	0.63^{***}	0.63^{***}	0.65^{***}	0.63^{***}	0.63^{***}	0.64^{***}
8/9	111	96	ns	ns	ns	ns	ns	ns	ns	ns	ns
8/15	117	99	0.51^{**}	0.51^{**}	0.51^{**}	0.50^{**}	0.50^{**}	0.50^{**}	0.50^{**}	0.50^{**}	0.50^{**}
						TSAVI			GNDVI		
		%	r^2								
7/11	82	91§				ns	ns	ns	ns	ns	ns
7/17	88	92§				ns	ns	ns	0.52^{**}	0.52^{**}	0.53^{**}
7/24	95	92				0.31^{*}	0.31^{*}	0.31^{*}	0.41^{**}	0.41^{**}	0.40^{**}
8/1	103	97				0.62^{***}	0.62^{***}	0.64^{***}	0.70^{***}	0.70^{***}	0.72^{***}
8/9	111	96				ns	ns	ns	ns	ns	ns
8/15	117	99				0.50^{**}	0.50^{**}	0.50^{**}	0.56^{***}	0.56^{***}	0.56^{***}

†trt = treatment, app = applied N, avail = available N

‡ DAP = Days after planting

§Calculated approximation using NDVI rather than approximation developed from images

*, **, *** Significance of overall F-values at $p \leq 0.05$, 0.01, 0.001.

660 nm explained 80% of soil-N differences. Like the individual wavebands, all five indices showed a decrease in the coefficient of determination and subsequent increase as the plants reflected N uptake from the July 29 application. Again, GNDVI responded the best and was the most sensitive to change in Treatment, Applied N, and Available N. While individual reflectance measurements showed significant separation of treatments (Table 12), the order did not necessarily follow treatment. The indices, beginning on July 17, seemed to minimize some of the confounding effects (Epiphanio and Huete, 1994) exhibiting better separation of treatment differences and in treatment order (Table 19). Just as with 2001, GNDVI detected the difference between three treatments as early as August 1, approximately 103 days following planting. Michigan carrots are generally harvested 80 to 180 days (USDA, 1999; Zandstra et al., 1986) after planting. On August 1 there would be plenty of time to correct nutrient deficiencies.

The 2001 early season measurements at the Experiment Station and Sandyland indicated all five indices performed equally according to the regression models. Though indices were generally significantly correlated with Available N, predictability of the models was too low to be relied on for N management, when canopy coverage averaged 19% at the Experiment Station and 63% at Sandyland by July 5. Mid and late season results at Sandyland, 2001 and 2002, indicated where canopies were healthy all five indices performed well. NDVI lagged slightly behind SAVI, SAVISL, and TSAVI as they all increased in significance over the season. GNDVI out performed the other indices in its assessment of soil-N both in the regression models and the mean separation of index values. Blackmer et al. (1994), Schepers et al (1992), and Schepers et al. (1996) also found that the "green band" together with NIR is better at showing the variability in leaf chlorophyll. At Sandyland, the only locations that attained full canopy, none of the indices plateaued as evidenced by the very high coefficients of determination. This phenomenon may be attributed to the lacy nature of the carrot canopy that may result in micro-views of the soil and shadows.

Table 19. Mean reflectance measurements as influenced by treatment or applied N at Sandyland, 2002, Sugar Snax variety.

Treatment	Index	July17	July 24	August 1	August 9	August 15
Kg ha^{-1}	(nm)	----------------	----------------	Index Value----------------	----------------	----------------
45	NDVI	ns	0.84b	0.87b	0.88b	0.89b
90		ns	0.88ab	0.89ab	0.89ab	0.90ab
135		ns	0.90a	0.90a	0.90ab	0.90ab
180		ns	0.91a	0.91a	0.91a	0.91a
p-value			0.005	0.005	0.01	0.002
45	SAVISL	ns	1.83b	1.90b	1.92b	1.94b
90		ns	1.92ab	1.95ab	1.95ab	1.96ab
135		ns	1.97a	1.97a	1.96ab	1.97a
180		ns	1.99a	1.99a	1.98a	1.99a
p-value			0.005	0.005	0.01	0.003
45	SAVI	ns	1.25b	1.29b	1.31b	1.32b
90		ns	1.30ab	1.32ab	1.33ab	1.33ab
135		ns	1.34a	1.34a	1.33ab	1.34a
180		ns	1.35a	1.35a	1.35a	1.35a
p-value			0.005	0.005	0.01	0.003
45	TSAVI	ns	0.83b	0.86b	0.87b	0.88b
90		ns	0.87ab	0.88ab	0.89ab	0.89ab
135		ns	0.89a	0.89a	0.89ab	0.89a
180		ns	0.90a	0.90a	0.90a	0.90a
p-value			0.006	0.005	0.01	0.003
45	GNDVI	0.78b	0.77b	0.79c	0.79b	0.80c
90		0.81ab	0.81ab	0.81bc	0.81ab	0.81bc
135		0.82a	0.83a	0.82ab	0.81ab	0.82ab
180		0.82a	0.84a	0.83a	0.83a	0.83a
p-value		0.024	0.002	0.001	0.003	0.001

Mean values with the same letters are not significantly different at p= 0.05 based on HSD.
p-value is that generated from overall F-ratio.
Results for Treatment and Applied N were the same.

In Season N Management: Reflectance vs Total N and Sap Nitrate

Carrot petioles were sampled at varied intervals during the two seasons and analyzed for total N and petiole sap NO^{-}_{3} content (Petiole-N) (Chapter 1, Table 5). These results representing the conventional measurement of plant response to N treatments were regressed against individual reflectance measurements and indices to determine if reflectance measurements depicted similar information about N treatment results as the conventional measurements. Spectral measurements taken on the three consecutive dates surrounding each petiole sampling date were compared to petiole analysis results. The purpose of comparing the three measurement dates was to find out when reflectance measurements were best correlated with the conventional samples: whether prior to physical sampling, at the same time, or following physical sampling.

Overall correlation of petiole samples to individual reflectance measurements and indices was insignificant until canopy coverage was greater than 90%. Only the Goliath variety showed earlier significance at 80 % canopy coverage (Table 20). It is distinguished by a darker green and more robust canopy than any of the other varieties included in the study. These results were comparable to the findings of Flowers et al. (2003b) who attributed such late correlation to the poor relationship between whole plant-N, without consideration for biomass, and spectral measurements. The extent of canopy coverage did not relate spectral measurements to N concentration. In this study, the N concentration, although not derived from whole plant tissue, appears to convey the same lack of correlation at lower canopy coverage. Statistical analysis indicated that blocking significantly impacted measured parameters. Canopy coverage of the Diamond Cut variety, during August and September was greater than 90 % and correlation between

Table 20. Linear regression coefficients of reflectance at individual wavelengths vs petiole-N; where petiole-N = total N content or petiole sap NO_3^- at the Montcalm Experiment Station, 2002, Goliath variety.

Petiole Sampling Date	Wavelength	Previous Date†		Sample Date†		Following Date†	
		TKN	Sap	TKN	Sap	TKN	Sap
(80% cov.)	(nm)	r^2					
7/25	510	0.24*	ns	0.24*	0.36*	ns	0.42**
	560	0.25*	ns	0.26*	0.40**	ns	0.49**
	610	0.24*	ns	0.24*	0.38**	ns	0.57***
	660	ns	ns	0.24*	0.36*	ns	0.46**
	710	0.27*	ns	0.25*	0.39**	ns	0.54**
	760	0.24*	ns	ns	0.37*	ns	ns
	810	0.28*	ns	ns	0.41**	ns	ns
	NDVI	0.25*	ns	ns	0.37*	ns	0.47**
	SAVISL	0.25*	ns	ns	0.37*	ns	0.46**
	SAVI	0.25*	ns	ns	0.37*	ns	0.47**
	TSAVI	0.26*	ns	ns	0.37*	ns	0.46**
	GNDVI	0.27*	ns	ns	0.39**	ns	0.46**
(94% cov.)	(nm)	r^2					
8/22	510	ns	ns	ns	0.27*	ns	0.43**
	560	ns	0.48**	0.27*	0.58***	0.43**	0.70***
	610	ns	0.25*	ns	0.39**	ns	0.53***
	660	ns	ns	ns	ns	ns	ns
	710	ns	0.45**	ns	0.44**	0.33*	0.65***
	760	ns	ns	ns	ns	ns	ns
	810	ns	ns	ns	ns	ns	ns
	NDVI	ns	ns	ns	ns	ns	ns
	SAVISL	ns	ns	ns	ns	ns	ns
	SAVI	ns	ns	ns	ns	ns	ns
	TSAVI	ns	ns	ns	ns	ns	ns
	GNDVI	ns	ns	ns	ns	ns	ns
(90% cov.)	(nm)	r^2					
9/9	510	0.48**	ns	ns	ns		
	560	0.72***	0.46**	ns	ns		
	610	0.43**	ns	ns	ns		
	660	ns	ns	ns	ns		
	710	0.60***	0.41**	ns	ns		
	760	0.38**	ns	0.24*	ns		
	810	0.36**	ns	0.24*	ns		
	NDVI	ns	ns	ns	ns		
	SAVISL	ns	ns	ns	ns		
	SAVI	ns	ns	ns	ns		
	TSAVI	ns	ns	ns	ns		
	GNDVI	ns	ns	ns	ns		

† Previous = Reflectance measurements one week before petiole sampling. Sampling date = Reflectance measurements on the same day as petiole sampling. Following = Reflectance measurements one week following petiole sampling.

*, **, *** Significance of overall F-values at p ≤0.05, 0.01, 0.001.

Table 21. Linear regression coefficients of reflectance at individual wavelengths vs petiole-N; where petiole-N = total N content or petiole sap NO_3^- at the Montcalm Experiment Station, 2001, Diamond Cut variety.

Petiole Sampling Date	Wavelength	Previous Date†		Sample Date†		Following Date†	
		TKN	Sap	TKN	Sap	TKN	Sap
(96% cov.)	(nm)	----------	----------	---------- r^2	----------	----------	----------
8/15	510	ns	ns	ns	ns	ns	ns
	560	ns	0.31*	ns	ns	ns	0.29*
	610	ns	ns	0.37**	0.33*	0.28*	0.38**
	660	ns	ns	ns	ns	0.28*	0.34**
	710	0.32*	0.36**	ns	0.38**	ns	0.31*
	760	ns	ns	ns	ns	ns	ns
	810	ns	ns	ns	ns	ns	ns
	NDVI	ns	ns	0.30*	ns	ns	ns
	SAVISL	ns	ns	0.30*	ns	ns	ns
	SAVI	ns	ns	0.30*	ns	ns	ns
	TSAVI	ns	ns	0.30*	ns	ns	ns
	GNDVI	ns	ns	0.51**	0.47**	ns	ns
(95% cov.)	(nm)	----------	----------	---------- r^2	----------	----------	----------
9/11	510	ns	0.32*	0.27*	ns		
	560	ns	ns	0.42**	0.33*		
	610	0.41**	0.46**	0.51**	0.44**		
	660	ns	0.26*	0.48**	0.43**		
	710	ns	ns	0.45**	0.34*		
	760	ns	ns	ns	0.26*		
	810	ns	ns	ns	ns		
	NDVI	ns	0.27*	0.39*	0.37*		
	SAVISL	ns	0.27*	0.37**	0.36*		
	SAVI	ns	0.27*	0.38**	0.37*		
	TSAVI	ns	0.27*	0.38**	0.37*		
	GNDVI	0.41**	0.55**	0.43**	0.36*		

† Previous = Reflectance measurements one week before petiole sampling. Sampling date = Reflectance measurements on the same day as petiole sampling. Following = Reflectance measurements one week following petiole sampling.

*, **, *** Significance of overall F-values at p $\leq$0.05, 0.01, 0.001.

reflectance and petiole samples increased over time until end of season (Table 21 and Table 22). Correlation was best at the September sampling date. At Sandyland correlation of reflectance measurements with Petiole-N was significant on only one date each year, July 19, 2001 and July 25, 2002 (Table 23 and Table 24). At that time coverage was 93% and 92%, respectively. Coverage was less than 90%, at earlier measurements and the last measurements were made when coverage was approximately 99%. Full canopy coverage was attained at Sandyland and reflectance appears to have saturated since none of the parameters at full coverage were significant at p ≤0.05.

Table 22. Linear regression coefficients of reflectance at individual wavelengths vs petiole-N; where petiole-N = total N content or petiole sap NO_3^- at the Montcalm Experiment Station, 2002, Diamond Cut variety.

Petiole Sampling Date	Wavelength	Previous Date†		Sample Date†		Following Date†	
		TKN	Sap	TKN	Sap	TKN	Sap
(97% cov.)	(nm)	r^2					
8/22	510	0.29*	ns	0.36*	ns	0.56***	0.36**
	560	0.71***	0.45**	0.71***	0.52**	0.77***	0.64***
	610	0.73***	0.44**	0.66***	0.43**	0.69***	0.67***
	660	ns	ns	ns	ns	0.38**	0.28*
	710	0.48**	0.64***	0.51**	0.60***	0.65***	0.76***
	760	0.33*	0.24*	ns	ns	ns	ns
	810	0.23*	0.24*	ns	ns	ns	ns
	NDVI	ns	ns	ns	ns	ns	ns
	SAVISL	ns	ns	ns	ns	ns	ns
	SAVI	ns	ns	ns	ns	ns	ns
	TSAVI	ns	ns	ns	ns	ns	ns
	GNDVI	ns	ns	0.49**	0.32*	0.36*	0.36**
(93% cov.)	(nm)	r^2					
9/9	510	ns	0.47**	ns	0.56***		
	560	ns	0.69***	ns	0.74***		
	610	ns	0.72***	0.25*	0.73***		
	660	ns	0.43**	ns	0.44**		
	710	0.33*	0.72***	0.37**	0.73***		
	760	ns	ns	ns	ns		
	810	ns	ns	ns	ns		
	NDVI	ns	0.25*	ns	ns		
	SAVISL	ns	ns	ns	ns		
	SAVI	ns	ns	ns	ns		
	TSAVI	ns	ns	ns	ns		
	GNDVI	ns	0.47**	ns	0.41**		

† Previous = Reflectance measurements one week before petiole sampling. Sampling date = Reflectance measurements on the same day as petiole sampling. Following = Reflectance measurements one week following petiole sampling.

*,**,*** Significance of overall F-values at p ≤0.05, 0.01, 0.001.

Petiole-N of the more robust Goliath variety correlated with reflectance on July 25, 2002, at 80% coverage. However, following July 25, further comparison to Petiole-N diminished in significance as the canopy senesced prematurely due to disease that affected biomass correlation to the NIR wavebands and all of the indices. Reflectance provided a small window of time where correlation with petiole-N was significant at $p \leq 0.05$; where canopy coverage was greater than 90% and less than 99% coverage.

Many of the studies referenced herein used leaf or whole plant samples as the physical comparison to reflectance. In this study, petioles were sampled because petiole nitrate content has been found to be a good indicator of the N status in carrot (Warncke, 1996). Petioles are often used as a reliable indicator of the N status in many crops (Hemphill and Jackson, 1982; Warncke, 1996; Walworth, 1998). However, petiole-N was better correlated with the reflectance measurements taken the week following

Table 23. Linear regression coefficients of reflectance at individual wavelengths vs petiole-N; where petiole-N = total N content or petiole sap NO_3^- at Sandyland, 2001, Asgrow B1 and Prime Cut 59 varieties.

Petiole Sampling Date	Wavelength	Previous Date†		Sample Date†		Following Date†	
		TKN	Sap	TKN	Sap	TKN	Sap
(93% cov.)	(nm)	----------	----------	---------- r^2	----------	----------	----------
7/19	510	ns	ns	ns	ns	0.46^{**}	0.52^{**}
	560	ns	ns	0.29^{*}	0.31^{*}	0.39^{**}	0.52^{**}
	610	ns	ns	0.30^{*}	0.33^{*}	0.58^{***}	0.65^{***}
	660	ns	ns	ns	ns	0.44^{**}	0.46^{**}
	710	ns	ns	0.27^{*}	ns	0.50^{**}	0.52^{***}
	760	ns	ns	ns	0.26^{*}	0.35^{*}	0.32^{*}
	810	ns	ns	ns	0.28^{*}	0.36^{**}	0.33^{*}
	NDVI	ns	ns	ns	ns	0.45^{**}	0.45^{**}
	SAVISL	ns	ns	ns	ns	0.45^{**}	0.44^{**}
	SAVI	ns	ns	ns	ns	0.45^{**}	0.45^{**}
	TSAVI	ns	ns	ns	ns	0.45^{**}	0.44^{**}
	GNDVI	ns	ns	0.33^{*}	0.41^{**}	0.51^{**}	0.53^{***}

† Previous = Reflectance measurements one week before petiole sampling. Sampling date = Reflectance measurements on the same day as petiole sampling. Following = Reflectance measurements one week following petiole sampling.

*, **, *** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$.

physical sampling, at all five locations. It appears that petiole samples may reflect the future condition of the canopy and that leaf samples may have been a more timely comparison to reflectance observations.

Table 24. Linear regression coefficients of reflectance at individual wavelengths vs petiole-N; where petiole-N = total N content or petiole sap NO_3^- at Sandyland, 2002, Sugar Snax variety.

Petiole Sampling Date	Wavelength	Previous Date†		Sample Date†		Following Date†	
		TKN	Sap	TKN	Sap	TKN	Sap
(92% cov.)	(nm)	r^2					
7/25	510	ns	ns	0.47^{**}	ns	0.83^{***}	0.55^{**}
	560	0.39^{**}	ns	0.53^{***}	ns	0.71^{***}	0.62^{***}
	610	0.43^{**}	ns	0.50^{**}	ns	0.80^{***}	0.56^{***}
	660	ns	ns	0.38^{**}	ns	0.62^{***}	0.28^{*}
	710	0.51^{**}	ns	0.51^{**}	ns	0.84^{***}	0.62^{***}
	760	ns	ns	ns	ns	ns	ns
	810	ns	ns	ns	ns	ns	ns
	NDVI	ns	ns	0.33^{*}	ns	0.46^{**}	ns
	SAVISL	ns	ns	0.32^{*}	ns	0.43^{**}	ns
	SAVI	ns	ns	0.32^{*}	ns	0.45^{**}	ns
	TSAVI	ns	ns	0.32^{*}	ns	0.45^{**}	ns
	GNDVI	ns	ns	0.35^{*}	ns	0.55^{**}	ns

† Previous = Reflectance measurements one week before petiole sampling. Sampling date = Reflectance measurements on the same day as petiole sampling. Following = Reflectance measurements one week following petiole sampling.
*, **, *** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$.

If a reflectance measurement is to provide in-season nutrient management, it should explain more than 50% of the variation between parameters. Reflectance measurements at 560, 610 and 710 nm exhibited the strongest correlation to Petiole-N in mid-to-late season. Of the three wavebands, reflectance at 560 and 610 nm were more often the best correlated with petiole-N, explaining as much as 77% of the differences in Diamond Cut (Table 22), and 80% of the differences in Sugar Snax (Table 24). Reflectance at 710 nm explained as much as 76 % of the differences in Diamond Cut (Table 22) and 84% Sugar Snax (Table 24).

NIR reflectance at 760 and 810 nm, associated with biomass, was weakly correlated with Petiole-N which also had an impact on the significance of the indices. GNDVI was the only index that, on occasion, could explain differences in Petiole-N where the coefficient of determination was greater than 50%. It was the significance of 560 nm in the formula that contributed to the strength of GNDVI. The remaining indices which rely on red reflectance at 660 nm, exhibited weak significance, but were unreliable for nutrient management. None of the indices performed as well as reflectance at individual wavebands, specifically, 560, 610, and 710 nm attributable to the weakness of reflectance at 810 nm.

It appears that in August at the Experiment Station and in July at Sandyland, when coverage was less than 99%, but greater than 90%, that the reflectance measurements explained similar information about canopy health as did Petiole-N. The respective timing represented mid-season when, if necessary, additional N amendments would have time to be taken up and utilized in the plant before harvest.

End of Season: Reflectance vs Selected Harvest Parameters

Reflectance measurements taken throughout the two seasons were compared to eight physical parameters measured at harvest. Those parameters were:

% N in Tops	N Uptake in Tops	Dry top Biomass	Yield
% N in Roots	N Uptake in Roots	Dry root Biomass	Root:Shoot

Not all parameters were significantly correlated to reflectance measurements or the indices calculated from reflectance; therefore, only the parameters showing more than sporadic significance were included in the following tables. % N in tops, N Uptake in Tops, Dry Top Biomass and Root:Shoot are the parameters concerned with healthy tops.

Individual Reflectance: Reflectance was not well correlated with % N in Tops (Table 25). Only in 2002, was reflectance of the Diamond Cut variety at the Experiment Station and Sugar Snax at Sandyland significantly correlated to % N in Tops, albeit low. Significance was focused at 560, 610 and 710 nm but it was not high enough to be predictable. Correlation to % N in the Tops which included the leaves as well as petioles was strongest in the visible bands. NIR reflectance at 760 and 810 nm, associated with biomass, was not significantly correlated with % N in Tops similar to the results for in-season Petiole-N.

Table 25. Linear regression coefficients of reflectance at individual wavelengths vs % N in harvested tops from selected locations.

Scan Date	DAP†	Ave Veg Cov %	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2002 Montcalm Experiment Station, Diamond Cut variety						
			r^2						
7/11	65	51§	ns	ns	ns	ns	ns	ns	ns
7/17	71	68	ns	ns	ns	ns	ns	ns	ns
7/24	78	86	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns
8/9	94	94	ns	0.27*	ns	ns	ns	ns	ns
8/15	100	98	ns	0.37*	0.27*	ns	0.54**	0.48**	0.50**
8/21	106	97	ns	0.47**	0.26*	ns	0.39**	ns	ns
8/30	115	88	ns	0.41**	0.35*	ns	0.40**	ns	ns
9/6	122	93	ns	0.42**	0.33*	ns	0.34*	ns	ns
			2002 Sandyland, Sugar Snax variety						
		%	r^2						
7/11	82	91§	ns	ns	ns	ns	ns	ns	ns
7/17	88	92§	0.33*	0.37*	0.44**	ns	0.35*	ns	ns
7/24	95	92	ns	ns	ns	ns	ns	ns	ns
8/1	103	97	0.46**	0.54**	0.37*	ns	0.35*	ns	ns
8/9	111	96	0.31*	0.26*	0.26*	ns	ns	ns	ns
8/15	117	99	ns	ns	ns	0.31*	ns	ns	ns

† DAP = Days after planting
§ Calculated approximation using NDVI rather than approximation developed from images.
*,**,*** Significance of overall F-values at p ≤0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

The % N in Roots (Table 26) was significantly correlated to reflectance at 560 and 610 nm in mid July, or the first of August. Preharvest predictability was evident at $r^2 > 0.50$ almost a month before harvest at the two Sandyland sites. A week before harvest correlation was strongly significant in all visible wavebands and reached a maximum correlation at wavebands 560 and 610 nm of $r^2 = 0.86$ followed by 710, 510, and 660 nm. It is interesting to note that 660 nm was not significantly correlated to % N in Tops where its response to chlorophyll was expected.

Reflectance correlated significantly with N Uptake in Tops (Table 27) at Sandyland as early as the first of August 2001 and mid July 2002. Predictability of the reflectance at 610, 560, and 510 nm was greater than 50 %. Here the combination of % N in Tops and Dry Top Biomass was more representative of the canopy than each of the two parameters separately (Tables 25 and 28). Dry Top Biomass was the dominant parameter for N Uptake in Tops. Reflectance from the Diamond Cut canopy; however, was better correlated to each of the separate parameters, % N and Dry Top Biomass. The resulting combination was sporadic in significance in N Uptake. The Goliath variety correlated best with mid-season Dry Top Biomass rather than % N. Where the canopy is healthy N Uptake in Tops may be a better in-season comparison than Petiole-N alone; the % N segment includes leaf -N and Petiole-N, and the biomass segment incorporates the coverage dimension into the measurement. Reflectance at 560, 610 and 710 nm provided the best overall correlation. Reflectance in the NIR wavebands was not well correlated.

While N Uptake in Roots, a combination of % N in Roots and Dry Root Biomass, is not a healthy tops issue, the strong significance with reflectance exhibited at Sandyland (Table 29) may be useful for monitoring the N content of storage roots used in food

Table 26. Linear regression coefficients of reflectance at individual wavelengths vs % N in harvested roots from selected locations.

Scan Date	DAP[†]	Ave Veg Cov	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2001 Montcalm Experiment Station, Diamond Cut variety						
		%	r^2						
7/12	65	35	ns	ns	ns	ns	ns	ns	ns
7/20	73	64	ns	ns	ns	ns	ns	ns	ns
7/26	79	85[§]	ns	ns	ns	ns	0.33^{*}	ns	ns
8/2	86	94	ns	ns	ns	ns	ns	ns	ns
8/9	93	97	ns	ns	0.30^{*}	ns	ns	ns	ns
8/17	101	96	0.39^{*}	ns	0.47^{**}	0.30^{*}	ns	ns	ns
9/6	121	95	ns	0.32^{*}	0.36^{*}	0.39^{*}	0.31^{*}	0.41^{**}	ns
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties						
		%	r^2						
7/12	83	89	0.29^{*}	0.28^{*}	0.26^{*}	ns	ns	ns	ns
7/19	90	93	ns	0.28^{*}	0.33^{*}	ns	ns	0.32^{*}	0.33^{*}
7/26	97	98[§]	0.41^{**}	0.37^{*}	0.45^{**}	0.35^{*}	0.42^{**}	0.38^{**}	0.39^{**}
8/2	104	99[§]	0.43^{**}	0.51^{**}	0.58^{***}	0.41^{**}	0.44^{**}	0.36^{*}	0.44^{**}
8/9	111	99	0.65^{***}	0.77^{***}	0.76^{***}	0.65^{***}	0.75^{***}	ns	ns
8/17	119	99	0.80^{***}	0.86^{***}	0.86^{***}	0.78^{***}	0.84^{***}	ns	ns
			2002 Montcalm Experiment Station, Diamond Cut variety						
		%	r^2						
7/11	65	51[§]	ns	ns	ns	ns	ns	ns	ns
7/17	71	68	0.32^{*}	0.33^{*}	0.30^{*}	0.30^{*}	ns	ns	ns
7/24	78	86	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns
8/9	94	94	ns	0.27^{*}	ns	ns	ns	ns	ns
8/15	100	98	ns	0.30^{*}	0.34^{*}	ns	0.46^{**}	ns	ns
8/21	106	97	ns	0.30^{*}	0.42^{**}	ns	0.25^{*}	ns	ns
8/30	115	88	0.26^{*}	0.27^{*}	0.39^{*}	0.33^{*}	0.32^{*}	ns	ns
9/6	122	93	0.31^{*}	0.27^{*}	0.35^{*}	0.44^{**}	0.32^{*}	ns	ns
			2002 Montcalm Experiment Station, Goliath variety						
		%	r^2						
7/11	65	46[§]	ns	ns	ns	ns	ns	ns	ns
7/17	71	66	ns	ns	ns	ns	ns	ns	ns
7/24	78	80	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	0.30^{*}	0.37^{*}	ns	0.30^{*}	ns	ns	ns
8/9	94	93	0.46^{**}	0.51^{**}	0.52^{**}	0.46^{**}	0.34^{*}	ns	ns
8/15	100	96	ns	ns	ns	ns	ns	ns	ns
8/21	106	94	ns	ns	ns	ns	0.28^{*}	ns	ns
8/30	115	87	ns	0.30^{*}	0.25^{*}	ns	0.27^{*}	ns	ns
9/6	122	90	ns	ns	ns	ns	ns	ns	ns

Table 26 (cont'd)

Scan Date	DAP†	Ave Veg Cov %	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2002 Sandyland, Sugar Snax variety						
			---r^2---						
7/11	82	91§	ns	ns	ns	ns	ns	ns	ns
7/17	88	92§	ns	0.26*	0.27*	ns	0.27*	ns	ns
7/24	95	92	ns	ns	ns	ns	ns	ns	ns
8/1	103	97	0.53**	0.66***	0.49**	0.28*	0.53**	ns	ns
8/9	111	96	0.46**	0.47**	0.46**	0.38*	ns	ns	ns
8/15	117	99	0.35*	0.34*	0.39**	0.44**	ns	ns	ns

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$. ns = Overall F-ratio is not significant

products. It may be an important topic for future studies. Dry Root Biomass (Table 30) showed very little correlation at any location, whereas % N in Roots (Table 26) and the resulting N Uptake in Roots (Table 28) was strongly correlated with reflectance in almost all wavebands. As early as August in 2001 and July in 2002, reflectance could explain greater than 50 % of the differences for N Uptake in Roots among N treatments. By harvest $r^2 > 0.70$ at 610 nm and $r^2 > 0.60$ at 510, 560, 660, and 710 nm.

Dry Top Biomass (Table 28) was best correlated where there was a healthy canopy as with the other parameters measured. While other parameters were better correlated with the visual wavebands, Dry Top Biomass as expected was also correlated to the NIR wavebands at 760 and 810 nm but saturated at 100 % coverage in 2001 Sandyland. In 2002 biomass of the Goliath variety at harvest exhibited significance to mid-season reflectance as though the recovering canopy was responding to mid season growth patterns. In early August, the Goliath variety had lost foliage due to disease, but later recovered.

While significant correlation to Dry Top Biomass at the Experiment Station in

Table 27. Linear regression coefficients of reflectance at individual wavelengths vs N uptake in harvested tops from selected locations.

Scan Date	DAP†	Ave Veg Cov %	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties						
			---------- r^2 ----------						
7/12	83	89	ns	ns	ns	ns	ns	ns	ns
7/19	90	93	ns	0.38^{*}	0.45^{**}	ns	0.28^{*}	ns	ns
7/26	97	98§	0.41^{**}	0.31^{*}	0.43^{**}	0.40^{**}	0.37^{*}	ns	ns
8/2	104	99§	0.52^{**}	0.53^{**}	0.56^{***}	0.48^{**}	0.48^{**}	ns	ns
8/9	111	99	0.55^{**}	0.61^{***}	0.59^{***}	0.56^{***}	0.61^{***}	ns	ns
8/17	119	99	0.61^{***}	0.62^{***}	0.61^{***}	0.58^{***}	0.61^{***}	ns	ns
			2002 Montcalm Experiment Station, Diamond Cut variety						
		%	---------- r^2 ----------						
7/11	65	51§	ns	ns	ns	ns	ns	ns	ns
7/17	71	68	ns	ns	ns	ns	ns	0.33^{*}	0.35^{*}
7/24	78	86	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns
8/9	94	94	ns	0.40^{*}	ns	ns	ns	ns	ns
8/15	100	98	0.30^{*}	0.43^{**}	0.31^{*}	ns	0.25^{*}	0.31^{*}	ns
8/21	106	97	ns	ns	ns	ns	ns	ns	ns
8/30	115	88	ns	0.27^{*}	ns	ns	ns	ns	ns
9/6	122	93	ns	ns	ns	ns	ns	ns	ns
			2002 Montcalm Experiment Station, Goliath variety						
		%	---------- r^2 ----------						
7/11	65	46§	ns	ns	ns	ns	ns	ns	ns
7/17	71	66	ns	ns	ns	ns	ns	0.30^{*}	0.31^{*}
7/24	78	80	ns	ns	ns	ns	ns	0.29^{*}	0.28^{*}
8/1	86	96	ns	0.29^{*}	0.30^{*}	0.29^{*}	ns	0.27^{*}	0.30^{*}
8/9	94	93	ns	ns	0.33^{*}	0.35^{*}	0.28^{*}	ns	ns
8/15	100	96	ns	ns	ns	ns	ns	ns	ns
8/21	106	94	ns	ns	ns	ns	ns	ns	ns
8/30	115	87	ns	ns	ns	ns	ns	ns	ns
9/6	122	90	ns	ns	ns	ns	ns	0.25^{*}	0.25^{*}
			2002 Sandyland, Sugar Snax variety						
		%	---------- r^2 ----------						
7/11	82	91§	ns	ns	ns	ns	ns	ns	ns
7/17	88	92§	0.32^{*}	0.38^{*}	0.46^{**}	ns	0.50^{**}	ns	ns
7/24	95	92	ns	ns	ns	ns	ns	ns	ns
8/1	103	97	0.65^{***}	0.48^{**}	0.54^{**}	0.35^{*}	0.44^{**}	ns	ns
8/9	111	96	0.45^{**}	ns	0.37^{*}	0.29^{*}	ns	ns	ns
8/15	117	99	ns	ns	ns	0.36^{*}	ns	ns	ns

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*,**,*** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$. ns = Overall F-ratio is not significant

Table 28. Linear regression coefficients of reflectance at individual wavelengths vs top biomass of harvested tops from selected locations.

Scan Date	DAP†	Ave Veg Cov	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2001 Montcalm Experiment Station, Diamond Cut variety						
		%	r^2						
7/12	65	35	ns	ns	ns	ns	ns	ns	ns
7/20	73	64	ns	ns	ns	ns	ns	0.27*	ns
7/26	79	85§	ns	ns	ns	ns	ns	ns	ns
8/2	86	94	0.28*	ns	ns	ns	ns	0.25*	0.27*
8/9	93	97	ns	ns	ns	ns	ns	ns	ns
8/17	101	96	ns	0.41**	ns	ns	0.33*	ns	ns
9/6	121	95	0.37*	0.58***	0.61***	0.48**	0.65***	0.33*	ns
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties						
		%	r^2						
7/5	76	63	ns	ns	ns	ns	ns	0.30*	0.28*
7/12	83	89	ns	0.27*	ns	ns	0.26*	0.35*	0.36*
7/19	90	93	ns	ns	0.27*	ns	ns	0.43**	0.45**
7/26	97	98§	0.42**	0.32*	0.47**	0.35*	0.38*	0.44**	0.47**
8/2	104	99§	0.31*	0.40*	0.41**	ns	0.43**	0.47**	0.54**
8/9	111	99	0.40*	0.48**	0.48**	0.45**	0.47**	ns	ns
8/17	119	99	0.62***	0.62***	0.63***	0.65***	0.58***	ns	ns
			2002 Montcalm Experiment Station, Diamond Cut variety						
		%	r^2						
7/11	65	51§	ns	ns	ns	ns	ns	0.36*	0.36*
7/17	71	68	ns	ns	ns	ns	ns	0.38*	0.42*
7/24	78	86	ns	ns	ns	ns	ns	0.32*	0.32*
8/1	86	96	ns	ns	ns	ns	ns	0.36*	0.33*
8/9	94	94	ns	0.29*	ns	ns	ns	ns	ns
8/15	100	98	0.41**	ns	ns	0.32*	ns	ns	ns
8/21	106	97	ns	ns	ns	ns	ns	ns	ns
8/30	115	88	ns	ns	ns	ns	ns	ns	ns
9/6	122	93	ns	ns	ns	ns	ns	ns	ns
			2002 Montcalm Experiment Station, Goliath variety						
		%	r^2						
7/11	65	46§	0.52**	0.52**	0.52**	0.52**	0.51**	ns	ns
7/17	71	66	0.41**	0.41**	0.40**	0.39**	0.34*	0.45**	0.45**
7/24	78	80	0.45**	0.48**	0.46**	0.45**	0.47**	0.37*	0.36*
8/1	86	96	0.39**	0.39**	0.46**	0.41**	0.41**	0.27*	ns
8/9	94	93	ns	ns	ns	ns	ns	ns	ns
8/15	100	96	ns	ns	ns	ns	ns	ns	ns
8/21	106	94	0.29*	ns	ns	ns	ns	ns	ns
8/30	115	87	ns	ns	ns	ns	ns	ns	ns
9/6	122	90	ns	ns	ns	ns	ns	0.47**	0.48**

Table 28 (cont'd)

Scan Date	DAP†	Ave Veg Cov %	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2002 Sandyland, Sugar Snax variety						
			r^2						
7/11	82	91§	ns	ns	ns	ns	ns	ns	ns
7/17	88	92§	ns	ns	ns	ns	0.27*	ns	ns
7/24	95	92	0.39**	ns	0.36*	0.38*	0.35*	ns	ns
8/1	103	97	0.30*	ns	0.27*	0.51**	ns	0.38*	0.36*
8/9	111	96	ns	ns	ns	0.33*	ns	0.46**	0.45**
8/15	117	99	ns	ns	ns	ns	ns	0.51**	0.51**

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at p ≤0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

2001 was sporadic at best, and correlation to Dry Root Biomass nonexistent, the combination of the two parameters in the form of Root:Shoot ratio (Table 31) were significantly correlated with reflectance at a level that could predict the partitioning of N treatments about a month before harvest. Reflectance at 560 and 710 nm, as it related to Root:Shoot, peaked about a week before harvest at $r^2 = 0.87$ and at 610 nm $r^2 = 0.83$. At Sandyland in 2001, the coefficient of determination could explain greater than 50 % of the differences as early as July 26, and even though it fluctuated, by season end $r^2 = 0.71$ at 510 nm and 0.70 at 560 nm. The Goliath variety (2002) exhibited a split correlation. Root:Shoot at harvest correlated to mid-season visible reflectance and to late season NIR reflectance.

The outcome of every site was different, and the relationship between the in-season reflectance measurements and the various harvest parameters revealed the importance of a healthy canopy throughout the season. In 2001 and 2002 various setbacks at the Experiment Station affected the correlation between reflectance and the harvest parameters. Correlation to reflectance was significant only for the Root:Shoot

Table 29. Linear regression coefficients of reflectance at individual wavelengths vs N uptake in harvested roots from selected locations.

Scan Date	DAP†	Ave Veg Cov	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties						
		%	---------- r^2 ----------						
7/12	83	89	ns	0.28^{*}	ns	ns	0.26^{*}	0.25^{*}	0.25^{*}
7/19	90	93	ns	ns	ns	ns	ns	0.41^{**}	0.41^{**}
7/26	97	$98^{\S}$	0.25^{*}	0.25^{*}	0.31^{*}	ns	0.30^{*}	0.49^{**}	0.50^{**}
8/2	104	$99^{\S}$	0.27^{*}	0.42^{**}	0.44^{**}	ns	0.40^{**}	0.50^{**}	0.52^{***}
8/9	111	99	0.51^{**}	0.62^{***}	0.62^{***}	0.54^{**}	0.61^{***}	ns	0.29^{*}
8/17	119	99	0.63^{***}	0.68^{***}	0.71^{***}	0.67^{***}	0.67^{***}	ns	ns
			2002 Montcalm Experiment Station, Diamond Cut variety						
		%	---------- r^2 ----------						
7/11	65	$51^{\S}$	0.35^{*}	0.40^{**}	0.39^{**}	0.38^{*}	0.41^{**}	ns	ns
7/17	71	68	0.48^{**}	0.50^{**}	0.49^{**}	0.50^{**}	ns	0.36^{*}	0.32^{*}
7/24	78	86	0.28^{*}	0.39^{*}	0.33^{*}	0.30^{*}	0.40^{*}	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns
8/9	94	94	ns	ns	ns	ns	ns	ns	ns
8/15	100	98	ns	ns	ns	ns	0.41^{*}	ns	ns
8/21	106	97	ns	ns	ns	ns	ns	ns	ns
8/30	115	88	ns	ns	ns	0.28^{*}	ns	ns	ns
9/6	122	93	0.33^{*}	ns	0.29^{*}	0.51^{**}	ns	ns	ns
			2002 Montcalm Experiment Station, Goliath variety						
		%	---------- r^2 ----------						
7/11	65	$46^{\S}$	ns	ns	ns	ns	ns	ns	ns
7/17	71	66	0.34^{*}	0.36^{*}	0.35^{*}	0.34^{*}	0.38^{*}	ns	ns
7/24	78	80	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns
8/9	94	93	ns	ns	ns	ns	ns	ns	ns
8/15	100	96	ns	ns	ns	ns	ns	0.39^{*}	0.39^{*}
8/21	106	94	ns	ns	ns	ns	0.27^{*}	ns	ns
8/30	115	87	ns	ns	0.25^{*}	0.29^{*}	ns	ns	ns
9/6	122	90	ns	ns	ns	ns	ns	ns	ns
			2002 Sandyland, Sugar Snax variety						
		%	---------- r^2 ----------						
7/11	82	$91^{\S}$	0.39^{**}	ns	0.58^{***}	0.54^{**}	0.25^{*}	0.31^{*}	0.30^{*}
7/17	88	$92^{\S}$	0.34^{*}	ns	0.46^{**}	0.51^{**}	ns	0.43^{**}	0.41^{**}
7/24	95	92	0.31^{*}	ns	0.33^{*}	0.36^{*}	ns	0.38^{*}	0.35^{*}
8/1	103	97	0.34^{*}	0.28^{*}	0.36^{*}	0.37^{*}	0.28^{*}	ns	0.26^{*}
8/9	111	96	ns	ns	ns	0.36^{*}	ns	0.34^{*}	0.35^{*}
8/15	117	99	ns	ns	0.29^{*}	0.49^{**}	ns	0.30^{*}	0.32^{*}

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*,**,*** Significance of overall F-values at p ≤0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

Table 30. Linear regression coefficients of reflectance at individual wavelengths vs root biomass of harvested roots from selected locations.

Scan Date	DAP†	Ave Veg Cov %	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2002 Montcalm Experiment Station, Goliath variety						
		%	---------- r^2 ----------						
7/11	65	46§	ns	ns	ns	ns	ns	ns	ns
7/17	71	66	ns	ns	ns	ns	ns	ns	ns
7/24	78	80	ns	ns	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns	ns	ns
8/9	94	93	ns	ns	ns	ns	ns	0.32*	0.31*
8/15	100	96	ns	ns	ns	ns	ns	0.34*	0.33*
8/21	106	94	ns	ns	ns	ns	ns	0.25*	0.25*
8/30	115	87	ns	ns	ns	ns	ns	ns	ns
9/6	122	90	ns	ns	ns	ns	ns	ns	ns
			2002 Sandyland, Sugar Snax variety						
		%	---------- r^2 ----------						
7/11	82	91§	ns	ns	0.40**	0.58***	ns	0.63***	0.63***
7/17	88	92§	ns	ns	ns	0.40**	ns	0.56***	0.54**
7/24	95	92	ns	ns	ns	ns	ns	0.46**	0.44**
8/1	103	97	ns	ns	ns	ns	ns	0.40*	0.40*
8/9	111	96	ns	ns	ns	ns	ns	0.35*	0.37*
8/15	117	99	ns	ns	ns	ns	ns	ns	ns

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at p ≤0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

ratio in 2001. During 2002, in-season reflectance measurements were only loosely predictive of the harvest parameters for either variety. Consequently, % N in Tops and % N in Roots for Diamond Cut were the only parameters that were consistently significant from August 9 to harvest. Dry Top Biomass and Root:Shoot ratio calculated for the Goliath variety significantly correlated with early reflectance through August 9 across all wavelengths. On August 9 reflectance could explain more than 50 % of the differences in % N in Roots. Following August 9, correlation diminished as the canopy senesced. Harvest was satisfactory but the canopy was unable to reflect that condition; therefore, it could not predict it.

Table 31. Linear regression coefficients of reflectance at individual wavelengths vs root:shoot ratio of biomass at harvest from selected locations.

Scan Date	DAP[†]	Ave Veg Cov %	510 nm	560 nm	610 nm	660 nm	710 nm	760 nm	810 nm
			2001 Montcalm Experiment Station, Diamond Cut variety						
		%	r^2						
6/13	36	0	ns	ns	ns	ns	ns	ns	ns
6/22	45	7	ns	ns	ns	ns	ns	ns	ns
6/28	51	11	ns	ns	ns	ns	ns	ns	ns
7/5	58	19	0.28*	ns	ns	0.28*	ns	ns	ns
7/12	65	35	0.42**	0.39*	0.42**	0.41**	0.37*	ns	ns
7/20	73	64	ns	ns	ns	ns	ns	0.26*	0.26*
7/26	79	85[§]	ns	ns	ns	ns	ns	0.28*	0.31*
8/2	86	94	ns	ns	ns	ns	ns	0.30*	0.32*
8/9	93	97	ns	0.49**	ns	ns	0.27*	ns	ns
8/17	101	96	0.45**	0.77***	0.68***	ns	0.59***	ns	ns
9/6	121	95	0.56***	0.87***	0.83***	0.67***	0.87***	ns	ns
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties						
		%	r^2						
6/13	54	21	ns	ns	ns	ns	ns	ns	ns
6/22	63	43	ns	ns	ns	ns	ns	ns	ns
6/28	69	63	ns	ns	ns	ns	ns	ns	ns
7/5	76	63	ns	ns	ns	ns	ns	ns	ns
7/12	83	89	0.33*	0.29*	0.27*	ns	ns	ns	ns
7/19	90	93	ns	0.36*	0.45**	ns	0.30*	0.27*	0.28*
7/26	97	98[§]	0.52**	0.39**	0.52**	0.56**	0.45**	0.42**	0.43**
8/2	104	99[§]	0.45**	0.47**	0.49**	0.46**	0.45**	0.29*	0.40*
8/9	111	99	0.48**	0.55**	0.54**	0.50**	0.53**	ns	ns
8/17	119	99	0.71***	0.70***	0.66***	0.67***	0.66***	ns	ns
			2002 Montcalm Experiment Station, Goliath variety						
		%	r^2						
7/11	65	46[§]	0.43**	0.41**	0.42**	0.43**	0.41**	ns	ns
7/17	71	66	0.60***	0.58***	0.56***	0.56***	0.57***	ns	ns
7/24	78	80	0.46**	0.46**	0.45**	0.45**	0.45**	0.28*	0.27*
8/1	86	96	0.45**	0.39*	0.50**	0.43**	0.39*	ns	ns
8/9	94	93	ns	ns	ns	ns	ns	ns	ns
8/15	100	96	ns	ns	ns	ns	ns	0.32*	0.30*
8/21	106	94	ns	ns	ns	ns	ns	0.29*	0.30*
8/30	115	87	ns	ns	ns	ns	ns	0.45**	0.46**
9/6	122	90	ns	ns	ns	ns	ns	0.58***	0.58***

[†] DAP = Days after planting

[§] Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at $p \leq 0.05$, 0.01, 0.001. ns = Overall F-ratio is not significant

In contrast, the 2001 and 2002 Sandyland sites showed better and more consistent correlation to reflectance for several of the harvest parameters. In 2001 reflectance was strongly correlated to % N in Roots, N Uptake in Tops and Roots, Dry Top Biomass, and Root:Shoot ratio. In 2002 correlation between reflectance and harvest parameters was similar but did not have the level of predictability experienced in 2001. Percent N in Tops, Dry Top Biomass and the combination of the two parameters, N Uptake in Tops, showed less consistency than in 2001. As discussed earlier, the effect of the N fertilizer applications appeared to be depleted before subsequent application and the canopy experienced temporary stress.

Selected Indices: The final test of the reflectance measurements was to correlate the indices against harvest parameters. At the Experiment Station in 2001, the individual reflectance measurements resulted in little correlation to harvest parameters; the indices also exhibited the lack of correlation. Results from the Experiment Station in 2001 only appear in Table 32.

None of the five locations exhibited significant correlation between the indices and % N in Tops. Due to the nature of the ratio-based indices and the wavebands sensitive to nutrient detection; this may be the expected outcome. These ratio-based indices depend in part on a visible band and in part on a NIR band. The absence of significant correlation to nutrient content in the NIR wavebands weakened the indices.

Consistent, significant correlation between the indices and % N in Roots (Table 32) was established only at the Sandyland 2001 location. Timing was about the same as individual wavebands, and continued to increase until harvest. However, none of the indices surpassed the individual wavebands for level of significance. NDVI and the soil adjusted variations performed about the same. GNDVI was the best correlated to % N in Roots.

Table 32. Linear regression coefficients of indices calculated from reflectance at individual wavelengths vs % N in harvested roots from selected locations.

Scan Date	DAP†	Ave Veg Cov	NDVI	SAVISL	SAVI	TSAVI	GNDVI
			2001 Montcalm Experiment Station, Diamond Cut variety				
		%	r^2				
7/20	73	64	ns	ns	ns	ns	ns
7/26	79	85§	ns	ns	ns	ns	ns
8/2	86	94	ns	ns	ns	ns	ns
8/9	93	97	ns	ns	ns	ns	ns
8/17	101	96	0.26*	0.26*	0.26*	0.26*	0.45**
9/6	121	95	0.36*	0.36*	0.36*	0.36*	ns
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties				
		%	r^2				
7/19	90	93	0.27*	0.29*	0.28*	0.28*	0.48**
7/26	97	98§	0.45**	0.45**	0.45**	0.45**	0.54**
8/2	104	99§	0.52**	0.54**	0.53**	0.52**	0.58***
8/9	111	99	0.64***	0.63***	0.63***	0.63***	0.74***
8/17	119	99	0.73***	0.71***	0.72***	0.72***	0.80***

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at p ≤0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

Yield, defined as harvest fresh weight, is similar to Dry Root Biomass, except for the water content. The results of regression analysis between reflectance and Yield at individual wavebands are not shown. Only NIR reflectance at 760 and 810 nm showed significant correlation that peaked in mid-season and then decreased until harvest. The indices exhibited more consistency (Table 33), but significant correlation diminished following mid-season. Notable is the difference in results between Yield and Dry Root Biomass (Table 34) and the apparent influence of water content on reflectance measurements. Only at Sandyland in 2002 were the results similar for both Yield and Dry Root Biomass. The remaining sites differed to such extent that none of the other locations are represented in both tables due to lack of significance.

Table 33. Linear regression coefficients of indices calculated from reflectance at individual wavelengths vs yield as Mg ha^{-1} fresh weight from selected locations.

Scan Date	DAP†	Ave Veg Cov %	NDVI	SAVISL	SAVI	TSAVI	GNDVI
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties				
		%	r^2				
6/13	54	21	ns	ns	ns	ns	ns
6/22	63	43	0.37^{*}	0.37^{*}	0.37^{*}	0.39^{**}	0.39^{**}
6/28	69	63	0.47^{**}	0.47^{**}	0.47^{**}	0.47^{**}	0.47^{**}
7/5	76	63	0.50^{**}	0.50^{**}	0.50^{**}	0.50^{**}	0.51^{**}
7/12	83	89	0.34^{*}	0.35^{*}	0.35^{*}	0.35^{*}	0.50^{**}
7/19	90	93	ns	ns	ns	ns	0.28^{*}
7/26	97	98§	ns	ns	ns	ns	0.29^{*}
8/2	104	99§	ns	ns	ns	ns	ns
8/9	111	99	ns	ns	ns	ns	ns
8/17	119	99	ns	ns	ns	ns	ns
			2002 Montcalm Experiment Station, Diamond Cut variety				
		%	r^2				
7/11	65	51§	0.42^{**}	0.42^{**}	0.42^{**}	0.42^{**}	0.42^{**}
7/17	71	68	0.33^{*}	0.34^{*}	0.33^{*}	0.34^{*}	0.33^{*}
7/24	78	86	0.33^{*}	0.33^{*}	0.33^{*}	0.33^{*}	0.34^{*}
8/1	86	96	ns	ns	ns	ns	ns
8/9	94	94	ns	ns	ns	ns	ns
8/15	100	98	ns	ns	ns	ns	ns
8/21	106	97	ns	ns	ns	ns	ns
8/30	115	88	ns	ns	ns	ns	ns
9/6	122	93	ns	ns	ns	ns	ns
			2002 Sandyland, Sugar Snax variety				
		%	r^2				
7/11	82	91§	0.63^{***}	0.63^{***}	0.63^{***}	0.63^{***}	0.63^{***}
7/17	88	92§	0.45^{**}	0.46^{**}	0.46^{**}	0.45^{**}	0.40^{**}
7/24	95	92	0.27^{*}	0.28^{*}	0.28^{*}	0.28^{*}	0.27^{*}
8/1	103	97	ns	ns	ns	ns	ns
8/9	111	96	ns	ns	ns	ns	ns
8/15	117	99	ns	ns	ns	ns	ns

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

$^{*, **, ***}$ Significance of overall F-values at p $\leq$0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

Table 34. Linear regression coefficients of indices calculated from reflectance at individual wavelengths vs root biomass of harvested roots from selected locations.

Scan Date	DAP†	Ave Veg Cov	NDVI	SAVISL	SAVI	TSAVI	GNDVI
			2002 Montcalm Experiment Station, Goliath variety				
		%	r^2				
8/15	100	96	ns	0.25*	ns	ns	ns
8/21	106	94	0.27*	0.28*	0.28*	0.27*	0.25*
8/30	115	87	0.25*	0.25*	0.25*	ns	ns
9/6	122	90	ns	ns	ns	ns	ns
			2002 Sandyland, Sugar Snax variety				
		%	r^2				
7/11	82	91§	0.64***	0.64***	0.64***	0.64***	0.64***
7/17	88	92§	0.49**	0.50**	0.49**	0.49**	0.44**
7/24	95	92	0.30*	0.31*	0.30*	0.31*	0.30*
8/1	103	97	ns	ns	ns	ns	ns
8/9	111	96	ns	ns	ns	ns	ns
8/15	117	99	ns	ns	ns	ns	ns

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at p $\leq$0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

Individual wavebands out performed the indices when compared to N Uptake in Tops (Table 27 vs Table 35) at the Sandyland 2001 location. Sandyland was the only location to exhibit the significance and consistent correlation in the visible wavebands

Table 35. Linear regression coefficients of indices calculated from reflectance at individual wavelengths vs N uptake in harvested tops from selected locations.

Scan Date	DAP†	Ave Veg Cov	NDVI	SAVISL	SAVI	TSAVI	GNDVI
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties				
		%	r^2				
7/12	83	89	ns	ns	ns	ns	ns
7/19	90	93	ns	ns	ns	ns	0.35*
7/26	97	98§	0.41*	0.40*	0.40*	0.40*	0.39*
8/2	104	99§	0.51**	0.50**	0.51**	0.51**	0.48**
8/9	111	99	0.48**	0.47**	0.48**	0.48**	0.52**
8/17	119	99	0.49**	0.48**	0.49**	0.49**	0.53**

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at p $\leq$0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

(Table 27) to result in the performance shown in Table 35. Again, visible reflectance was significantly correlated while NIR reflectance was insignificant or loosely correlated ultimately due to canopy biomass conditions.

When compared to N Uptake in Roots (Table 36), the indices out performed individual reflectance (Table 28), specifically evident at both the 2001 and 2002 Sandyland locations. The synergy provided by the significance of both the visible and NIR wavebands was apparent, especially when compared to the results of the Experiment Station. In addition, the indices exhibited more consistency throughout the season as multiplicative effects were minimized (Epiphanio and Huete, 1994).
In 2001 GNDVI out performed the red reflectance indices; however, in 2002 all indices performed equally well. Significance was evident at mid-season when canopy coverage was approximately 90 %, and continued to increase in significance until harvest.

Indices, when compared to Dry Top Biomass (Table 37) of the harvested tops, showed the same synergy as N Uptake in Roots. Indices performed slightly better and significance was more consistent over time than individual reflectance but followed the same trends. The indices were not well correlated to Dry Root Biomass (Table 34). The table is included because of the function Dry Root Biomass has as part of N Uptake in Roots and the following discussion of Root:shoot ratio. In addition, it shows the strength of the NIR (Table 30) wavebands as they relate to the indices.

Correlation of the indices to the Root:shoot ratio (Table 38) offered no new surprises. Overall, significance mirrored the trends set by the individual reflectance. Where NIR reflectance was significant along with the applicable visible bands, the indices were better correlated and the coefficient of determination could explain more of

Table 36. Linear regression coefficients of indices calculated from reflectance at individual wavelengths vs N uptake in harvested roots from selected locations.

Scan Date	DAP[†]	Ave Veg Cov %	NDVI	SAVISL	SAVI	TSAVI	GNDVI
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties				
		%	r^2				
7/12	83	89	ns	ns	ns	ns	ns
7/19	90	93	ns	0.27^{*}	0.26^{*}	0.26^{*}	0.47^{**}
7/26	97	98[§]	0.43^{**}	0.44^{**}	0.43^{**}	0.44^{**}	0.57^{***}
8/2	104	99[§]	0.38^{*}	0.40^{**}	0.39^{**}	0.39^{**}	0.55^{**}
8/9	111	99	0.65^{***}	0.65^{***}	0.65^{***}	0.65^{***}	0.73^{***}
8/17	119	99	0.71^{***}	0.71^{***}	0.71^{***}	0.71^{***}	0.73^{***}
			2002 Montcalm Experiment Station, Diamond Cut variety				
		%	r^2				
7/11	65	51[§]	0.26^{*}	0.26^{*}	0.26^{*}	0.25^{*}	0.25^{*}
7/17	71	68	ns	ns	ns	0.25^{*}	ns
7/24	78	86	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns
8/9	94	94	ns	ns	ns	ns	ns
8/15	100	98	ns	ns	ns	ns	ns
8/21	106	97	0.29^{*}	0.29^{*}	0.29^{*}	0.29^{*}	0.31^{*}
8/30	115	88	ns	ns	ns	ns	ns
9/6	122	93	0.36^{*}	0.31^{*}	0.34^{*}	0.32^{*}	0.29^{*}
			2002 Montcalm Experiment Station, Goliath variety				
		%	r^2				
7/11	65	46[§]	ns	ns	ns	ns	ns
7/17	71	66	ns	ns	ns	ns	ns
7/24	78	80	ns	ns	ns	ns	ns
8/1	86	96	ns	ns	ns	ns	ns
8/9	94	93	0.29^{*}	0.28^{*}	0.28^{*}	0.28^{*}	ns
8/15	100	96	0.31^{*}	0.34^{*}	0.32^{*}	0.32^{*}	0.37^{*}
8/21	106	94	0.29^{*}	0.29^{*}	0.29^{*}	0.29^{*}	0.30^{*}
8/30	115	87	ns	ns	ns	ns	ns
9/6	122	90	ns	ns	ns	ns	ns
			2002 Sandyland, Sugar Snax variety				
		%	r^2				
7/11	82	91[§]	0.47^{**}	0.47^{**}	0.47^{**}	0.47^{**}	0.47^{**}
7/17	88	92[§]	0.50^{**}	0.50^{**}	0.50^{**}	0.49^{**}	0.50^{**}
7/24	95	92	0.38^{*}	0.38^{*}	0.38^{*}	0.38^{*}	0.37^{*}
8/1	103	97	0.38^{*}	0.37^{*}	0.37^{*}	0.37^{*}	0.40^{**}
8/9	111	96	0.42^{**}	0.42^{**}	0.42^{**}	0.42^{**}	0.42^{**}
8/15	117	99	0.50^{**}	0.50^{**}	0.50^{**}	0.50^{**}	0.46^{**}

[†] DAP = Days after planting

[§] Calculated approximation using NDVI rather than approximation developed from images.

*,**,*** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$. ns = Overall F-ratio is not significant

Table 37. Linear regression coefficients of indices calculated from reflectance at individual wavelengths vs top biomass of harvested tops from selected locations.

Scan Date	DAP†	Ave Veg Cov	NDVI	SAVISL	SAVI	TSAVI	GNDVI
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties				
		%	r^2				
7/12	83	89	ns	0.25*	0.25*	0.25*	0.32*
7/19	90	93	0.37*	0.40*	0.38*	0.38*	0.58***
7/26	97	98§	0.54**	0.55**	0.54**	0.54**	0.60***
8/2	104	99§	0.43**	0.45**	0.44**	0.44**	0.53**
8/9	111	99	0.52**	0.52**	0.52**	0.57**	0.56**
8/17	119	99	0.63***	0.62***	0.63***	0.63***	0.62***
			2002 Montcalm Experiment Station, Goliath variety				
		%	r^2				
7/11	65	46§	0.51**	0.51**	0.51**	0.51**	0.51**
7/17	71	66	0.41**	0.41**	0.41**	0.41**	0.42**
7/24	78	80	0.45**	0.45**	0.45**	0.44**	0.46**
8/1	86	96	0.42**	0.42**	0.42**	0.42**	0.42**
8/9	94	93	ns	ns	ns	ns	ns
8/15	100	96	ns	ns	ns	ns	ns
8/21	106	94	ns	ns	ns	ns	ns
8/30	115	87	ns	ns	ns	ns	ns
9/6	122	90	0.39**	0.42**	0.40**	0.42**	0.49**
			2002 Sandyland, Sugar Snax variety				
		%	r^2				
7/11	82	91§	ns	ns	ns	ns	ns
7/17	88	92§	ns	ns	ns	ns	ns
7/24	95	92	0.37*	0.36*	0.37*	0.37*	0.34*
8/1	103	97	0.41**	0.41**	0.41**	0.41**	0.33*
8/9	111	96	0.37*	0.38*	0.38*	0.38*	0.30*
8/15	117	99	ns	ns	ns	ns	ns

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at p ≤0.05, 0.01, 0.001. ns = Overall F-ratio is not significant

the differences.

The importance of a healthy canopy throughout the season is supported by the varied results obtained when spectral measurements were compared to the various parameters measured at the five study locations. Harvest parameters indicative of the N status of the tops were % N in Tops, N Uptake in Tops, Dry Top Biomass, and

Table 38. Linear regression coefficients of indices calculated from reflectance at individual wavelengths vs root:shoot ratio of biomass at harvest from selected locations.

Scan Date	DAP†	Ave Veg Cov %	NDVI	SAVISL	SAVI	TSAVI	GNDVI
			2001 Montcalm Experiment Station, Diamond Cut variety				
		%	r^2				
7/5	58	19	0.39*	0.40*	0.40*	0.40*	0.38*
7/12	65	35	0.59**	0.59**	0.59**	0.59**	0.60**
7/20	73	64	ns	ns	ns	ns	ns
7/26	79	85§	ns	ns	ns	ns	ns
8/2	86	94	ns	ns	ns	ns	ns
8/9	93	97	ns	ns	ns	ns	ns
8/17	101	96	ns	ns	ns	ns	0.26*
9/6	121	95	0.46**	0.42**	0.44**	0.43**	0.58***
			2001 Sandyland, Asgrow B1 and Prime Cut 59 varieties				
		%	r^2				
7/5	76	63	ns	ns	ns	ns	ns
7/12	83	89	ns	ns	ns	ns	ns
7/19	90	93	0.47**	0.48**	0.48**	0.48**	0.63***
7/26	97	98§	0.61***	0.61***	0.61***	0.61***	0.59***
8/2	104	99§	0.65***	0.66***	0.65***	0.65***	0.59***
8/9	111	99	0.55**	0.55**	0.55**	0.55**	0.59***
8/17	119	99	0.64***	0.62***	0.63***	0.63***	0.66***
			2002 Montcalm Experiment Station, Goliath variety				
		%	r^2				
7/11	65	46§	0.43**	0.43**	0.43**	0.43**	0.42**
7/17	71	66	0.52**	0.52**	0.52**	0.51**	0.52**
7/24	78	80	0.44**	0.44**	0.44**	0.44**	0.44**
8/1	86	96	0.39*	0.38*	0.38*	0.38*	0.32*
8/9	94	93	ns	ns	ns	ns	ns
8/15	100	96	ns	ns	ns	ns	ns
8/21	106	94	ns	ns	ns	ns	ns
8/30	115	87	0.29*	0.32*	0.30*	0.30*	0.37*
9/6	122	90	0.35*	0.38*	0.36*	0.36*	0.45**

† DAP = Days after planting

§ Calculated approximation using NDVI rather than approximation developed from images.

*, **, *** Significance of overall F-values at $p \leq 0.05, 0.01, 0.001$. ns = Overall F-ratio is not significant.

Root:Shoot ratio. The biomass segment of N Uptake made an important contribution and where the canopies suffered problems, biomass was not consistently indicative of plant response to N. The % N portion, although important, did not appear to affect correlation to the same extent as biomass. The Root:Shoot ratio showed significant correlation where canopies were healthy or recovering. Again, the most important factor appeared to be the top biomass. Overall correlation to those parameters important to healthy tops was best measured at 510, 560, 610, and 710 nm.

The canopy also showed promise as a predictive tool for monitoring N content of roots. Reflectance was correlated to % N in Roots at least sporadically at all locations. At the 2001 Sandyland site, reflectance at 560 and 610 nm explained as much at 86% of the differences in N content followed by reflectance at 710 nm where $r^2 = 0.84$. Future studies focused on the storage roots may show that canopy reflectance can be an important tool for managing N in the roots as well as tops.

Conclusion

This study has shown that remote sensing may work for the vegetable industry, especially for crops that are typically mechanized, such as carrot. It was intended to explore the possibility that in-season N management for quality carrot tops could be successful using remote sensing. To that end, the first objective was to determine which wavelengths correlate to the physical parameters typically used to evaluate the health of the carrot crop.

The visible wavebands, even where there was plant disease, were able to provide insight about the crop response to N availability. The visible bands centered at 560 and 710 nm were the earliest to correlate with Soil-N and generally remained significant throughout the season explaining as much as 90% of the difference between treatments where the canopy was healthy. These results are in agreement with the findings of Thomas and Gausman (1977), Blackmer et al. (1994), Blackmer et al. (1996a, 1996b), and Masoni et al. (1996) in agronomic crops. In carrot, wavebands centered at 510 and 610 were also significantly correlated to the physical parameters analyzed and may prove to be important to future studies in carrot.

NIR reflectance at 760 and 810 nm was weakly correlated with plant N status when the plants were affected by variables other than N treatments and when the canopy reached full coverage. This phenomenon also had an impact on the usefulness of the indices which were out performed by visible reflectance when NIR reflectance was not significantly correlated to the parameter of interest and correlation at 560 or 660 nm was weak ($r^2 \leq 0.40$).

Indices covered in this study are ratio based, subject to the significance exhibited by two wavebands, a visible and a near infrared. NDVI, SAVI, SAVISL, and TSAVI use the same two wavebands: the visible band at 660 nm and the near infrared band at 810 nm. The only difference between the four indices is the handling of the soil background. NDVI has no adjustment for soil background, and the three SAVI-type indices are adjusted according to equations 5 and 6 (pages 58 and 59). Soil adjusted indices were designed to be more sensitive to changes in NIR (Epiphanio and Huete, 1994) influenced by vegetative cover and vigor (Flowers et al., 2003b). While NDVI lagged slightly behind the others in carrot, it was no less sensitive to canopy coverage than the SAVI-type indices. The typical density of carrot planting and thickness of the maturing canopy may hamper the NIR indicator of vegetative cover and vigor, where biomass differences may be nonexistent. The sensitivity of any of the indices in carrot seemed to be dependant on two factors: 1) the amount of soil in the pixel; and 2) the dominance shown by the visible wavelength, the indicator of nutrient status. GNDVI, like NDVI, does not include a soil adjustment, and the visible waveband was replaced with reflectance at 560 nm, where reflectance was generally more dominant as a nutrient status indicator and therefore, out performed the other indices in its assessment of N status. GNDVI was the only index that on occasion could explain differences in Petiole-N where the coefficient of determination was greater than 50%. These results are in agreement with Blackmer et al. (1994), Schepers et al (1992), and Schepers et al. (1996).

Where full canopy existed, none of the indices plateaued indicated by associated high coefficients of determination. This relationship may be attributed to the nature of the canopy, made up of layers of lacy structured leaves resulting in multilayer shadowing and possible micro-views of the soil. In addition, it may be due to the manner in which the "L" adjustment in certain indices was used. The maximum value of NDVI was 0.91, as expected in dense canopy (Aparicio et al., 2000; Epiphanio and Huete, 1994). TSAVI also stayed within the range of 0 to 1 at a maximum value of 0.91 in full canopy similar to NDVI. SAVISL and SAVI exceeded their expected range of 0 to1 at 1.99 and 1.35, respectively. Apparently, the use of a static "L" in dense canopies influences the range restrictions built into the equation, but allows those indices to continue to increase where they may have saturated or plateaued.

The second objective was to determine if reflectance could be used as an in-season management tool. Soil-N status was significantly correlated to 560 and 710 nm at approximately 89 to 94% vegetative cover, 93 to 94 days after planting and generally after the second N fertilizer application until harvest. This was at least 35 days before harvest, which was enough time to use intervention strategies to fertilize without accumulating excess N in the storage root. In addition, the influence of soil N treatments on the crop canopy showed significant correlation to N treatments in about two weeks after fertilizer application and remained constant or decreased as the N application was "used-up" by the plants in about 25 days.

In carrot, remote sensing research is in the early stage. Correlation between reflectance in certain wavebands has been established, but critical reflectance values used to estimate N fertilizer requirements, whether as individual wavebands or indices, have not been determined. For example, while 560 nm seems to be the best individual waveband, critical values may be linked to relative reflectance measurements due to the numerous shades of healthy green reflected by the many varieties of carrot used in production. It is important to note that remote sensing used to manage N will be useful in well managed fields where the canopy is healthy and the fields are free of weeds.

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Chapter III

SAVI Determination in Carrots: Comparing Constant and Dynamic Soil Adjustment Factors

Introduction

Reliable interpretation of reflectance measurements of vegetation in incomplete canopies is confounded by the influence of the soil background. The sun angle, view angle and atmospheric conditions that alter remote sensing spectral signatures are increasingly corrected by improvements in atmospheric models. However, the canopy background "brightness" that affects the vegetation indices (VI) is not easily corrected and must be handled within the VI equation itself (Gao et al., 2000).

Soil background has an impact on vegetation parameters because the spectral response of soil generally rises gradually from the blue wavebands across the visible and near infrared (NIR) part of the spectrum. The spectral response of vegetation in the visible bands is punctuated with peaks and valleys, as the reflectance measurements reveal signature absorption bands of chlorophyll pigments. In NIR, vegetative responses rise above the spectral response of soil. When a pixel contains both soil and vegetation information, the spectral responses associated with differences in vegetative parameters, such as crop development or in-season water and N management, are diluted. In addition, the soil background is variable and sensitive to soil type and wetting and drying cycles (Huete, 1987a; Li et al., 2001). For example, Stoner and Baumgardner (1981) examined a sample of 485 soils, each with a distinct spectral signature, and identified five distinct soil reflectance curve patterns classified by the curve shape and absorption bands.

The five curves had certain characteristics pertaining primarily to organic matter and iron oxide content. They found the spectral signatures for all 485 soils reflected the specific spectral properties of some of the same traits that identify the taxonomic suborders to which these soils belong, as defined by the Soil Taxonomy (1975). In addition, Rondeaux et al. (1995) found that organic matter adds important variation to the spectral signature and generally reduces reflectance measurements throughout the measured spectrum. In general, soil type has a greater impact on the spectral properties of the soil background than either moisture or soil roughness by as much as one order of magnitude (Rondeaux et al., 1995). Changes in moisture or roughness are revealed as movement up and down the same soil line: the plot of NIR reflectance versus red reflectance. The soil type will alter the slope of the soil line. For example, where the crop represented a 37% soil cover, overall reflectance was almost three times greater on light colored soils than on darker soils (Ma et al., 2001).

A major goal in remote sensing research of vegetation canopies is the separation of spectral changes due to vegetative response from those attributed to soil background; especially where studies involve spatial and temporal changes (Huete, 1987a). Soil adjusted vegetation indices, developed for the purpose of correcting the background "brightness" have produced varying degrees of success depending on the canopy density. The objective of this study is to 1) determine whether the fc model (Qi, 2000), described below, is a reasonable estimate of canopy coverage; and 2) determine whether fc can be successfully substituted in SAVI as $L = (1-fc)$ as a dynamic soil adjustment factor when the amount of vegetation is unknown.

Literature Review

Huete (1987a), and later Gao et al. (2000) modeled the relationship between canopy response and underlying bare soil reflectance using the following equation where:

$$dm = E_o r_s t_c^2 + E_o r_c \qquad [1]$$

- dm = the composite spectra of the soil-canopy mixture,
- $E_o r_s t_c^2$ = the soil dependent component: the product of E_o (global irradiance), r_s (soil spectra), and t_c^2 (the slope that represents the upward and downward transmittance of irradiance through the canopy),
- $E_o r_c$ = the vegetative component.

Huete (1987a) found that the relationship was linear (Eq. 1) for each waveband, indicating that first order soil-vegetation interaction was sufficient to explain measured spectral response. A variation of Eq. 1 was set forth in another study by Huete (1987b) where:

$$r_c = r_v + b_1 r_s \qquad [2]$$

- r_c = composite canopy reflectance,
- r_v = vegetative component reflectance,
- r_s = bare soil reflectance, and
- b_1 = slope (transmittance).

Gao et al. (2000), and Huete (1987a, 1987b), comparing the usefulness of various vegetation indices in eliminating soil background contamination, used Eq. 1 and 2 to separate the composite reflectance measurements. They found this is only possible when the soil reflectance is known. In their methodology, canopy spectra were measured repeatedly over a developing cotton canopy to measure the influence of progressively greater coverage over four different soil types. On each measurement occasion, the four soils on trays were interchanged under the canopy using a support frame. Using Eq.1 and 2, canopy responses were plotted against the bare soil spectra, separately for each wavelength. When the canopy coverage is held constant against various soil backgrounds, the response is linear. As canopy coverage increases, the slope changes, ranging from 1 when vegetation coverage is zero to 0 at 100% canopy coverage. The y-intercept represents the point at which influence from the soil background is zero. The slope of the line represents the two-way global canopy transmittance, t_c^2 (Huete, 1987a).

If the slope, t_c^2, of each measurement is plotted against the measured spectrum, the appearance of the resulting spectral signatures increasingly resembles that of a vegetation signature as the canopy coverage increases. In Huete (1987a), the likeness was most pronounced at 90% canopy coverage. At canopy coverage denser than 90%, transmittance values approach zero for all wavebands, producing zero slope (Huete, 1987a). Therefore, the soil component is equal to the soil reflectance multiplied by the slope, t_c^2, and has the appearance of both underlying bare soil as well as the overlying transmitted vegetation signature. It consists of all radiant flux reaching the sensor above, that has interacted with the soil background including that which is reflected from the soil and has been scattered by the plant canopy before reaching the sensor (Huete, 1987a). By subtracting the soil component from the composite reflectance, the derived plant spectra represent only the vegetative component, free of soil and the backscatter from the canopy.

Red and NIR wavebands are usually associated with vegetative growth. Of the two, NIR is most sensitive to increases in canopy coverage (Gao et al., 2000; Huete, 1987a), but response to changes in vegetation is dependent on underlying soil brightness. Bright soils tend to decrease modeled canopy reflectance, while darker soils increase it (Gao et al., 2000). NIR (760 to 900 nm) response represents several layers of canopy as a result of low absorption by leaf elements and high reflectance and transmittance. Soil and plant spectral interaction is strong in this area because of high NIR flux scattering within the vegetative canopy (Huete, 1987a). The red waveband (630-690 nm) reflectance from the canopy generally decreases with increasing vegetative coverage (Gao et al., 2000), and may only represent the uppermost leaf layers of the canopy due to the intense absorption by chlorophyll pigments. The red waveband is relatively insensitive to changes in vegetative coverage amounts (Huete, 1987a) compared to NIR. In fact, the soil spectral contribution in red is primarily from exposed soil surfaces reflecting direct solar radiation and diffused skylight (Huete, 1987a). Gao et al. (2000) also notes that visible bands, in general, provide very little discrimination and most changes in visible bands are associated with soil background differences instead of vegetation.

The use of NIR or red spectral bands alone does not account for seasonal sun angle differences (Ma et al., 2001). Vegetation indices have been developed to account for spectral and temporal changes; the choice and suitability of which is generally determined by the sensitivity to the characteristics of interest (Gao et al., 2000). The optimal vegetation index should be invariant to the soil dependent component and yet sensitive to spectral differences attributed to the vegetation component (Huete, 1987a).

Two well-known indices featured in this study are discussed herein.

The Normalized Difference Vegetation Index (NDVI), first developed in 1979 by Compton J.Tucker, a NASA researcher, is a measure of the green, leafy density of vegetation (NASA, 2003). NDVI utilizes the NIR and red wavebands in the following equation where:

$$NDVI = (NIR - red)/(NIR + red) \qquad [3]$$

Ma et al. (2001) regarded NDVI as one of the best indices at predicting yield and midseason fertilizer amendments. Rondeaux et al. (1995) found NDVI well correlated to vegetation amount until it saturates at full canopy coverage. It is useful for yielding biophysical relationships applicable across varying canopy types; however, NDVI sensitivity to soil optical properties affects these relationships and requires knowledge of the soil reflectance for use in interpretation of measurements (Gao et al., 2000; Rondeaux et al., 1995). When Gao et al. (2000) removed the soil background according to Eq.1; NDVI exhibited very little sensitivity to vegetation, approaching saturation throughout the entire range of canopy leaf area index (LAI). The inclusion of a soil background restored an exponential dynamic range of NDVI, but in a manner dependent on the background optical properties (Gao et al., 2000). Gao et al. (2000) further stated NDVI is not only background sensitive, but most of its dynamic range occurs only with the presence of a soil background: the brighter the background the greater the dynamic range. They found little variation between the measurements of broadleaf crops and grasses. The index is more sensitive to soil background than canopy type (Gao et al., 2000). Huete (1987b) found that NDVI of the vegetation component (zero soil) achieved the necessary invariance to differences in the solar sun angle, but once again, it was the soil component contribution that limited its usefulness as a vegetation index and induced strong anisotropic (directional) canopy behavior.

A number of soil adjusted vegetation indices have been developed: many are variations of the Soil Adjusted Vegetation Index (SAVI) developed by Huete (1988) where:

$$SAVI = (1 + L) * (NIR - R) / (NIR + R + L) \quad [4]$$

L = a soil adjustment factor that diminishes as the vegetation grows denser. According to Rondeaux et al. (1995), the term (1+L) is used to maintain the dynamic range of the index between -1.0 and 1.0; however, the term was eliminated in their use of the equation. SAVI is a significant improvement over earlier models. It is more reliable and less noisy than NDVI. Rondeaux et al. (1995) tested SAVI and several of its variations, the Modified Soil Adjusted Vegetation Index (MSAVI), the Transformed Soil Adjusted Vegetation Index (TSAVI), and the Two-axis Vegetation Index, by putting different soil optical properties into a vegetation bidirectional reflectance model and examining the sensitivity of the various indices to the soil. They found that SAVI has one of the lowest standard deviations when vegetation coverage is low, remains quite constant over the mid range of canopy coverage, and improves above 80% vegetation coverage. SAVI was less definitive between 50% and 80% canopy coverage than other indices in the study.

Most of the present indices are related to the soil line. The optical properties of the 26 soils used in the study by Rondeaux et al. (1995) were representative of five basic types: fine sand, clay, peat, pozzolana, and pebbles. Even with the improvements of SAVI, they found that using one universal soil line to account for all soil types rendered an inadequate depiction of the vegetative canopy. Separating the 26 soils into mineral and organic categories revealed that the slope of the organic soil line was twice that of the mineral soils. Applying the appropriate soil line improved the outcome of the indices. Rondeaux et al. (1995) tested several values for L in the SAVI index and found 0.16 or 0.20 best at minimizing the standard deviation over the full canopy range, and proposed that one of these values be adopted for agricultural applications. However, when used where vegetative coverage was less than 50%, variances were somewhat higher than when L was defined as 0.5. The choice of L in SAVI-type indices appears to be critical in minimizing the soil background effect (Rondeaux et al., 1995).

Huete (1988) noted that L, as used in SAVI, should diminish as canopy density increases. Therefore, when measurements are taken throughout the growing season the definition of L should change as the canopy changes. Instead, L is typically assigned the value of 0.5, which is a reasonable approximation when the amount of soil in the scene is unknown (US Water Conservation Laboratory, 2003). A dynamic L would be more attractive if quantitative determination of changing canopy coverage did not require additional measurements such as Leaf Area Index (LAI). If canopy coverage could be estimated using the model described below, and the estimate substituted for L as $(1-fc)$ in Eq. 4, it would eliminate additional measurements required for accurate coverage assessment.

A fractional vegetation coverage model developed by Qi et al. (2000) was intended to be used as an alternative processing technique to circumvent atmospheric effects of satellite images in arriving at biophysical properties of land surfaces. Atmospheric and bidirectional correction procedures are available, but often the ancillary data about the concurrent atmospheric conditions are limited. A practical technique in resolving atmospheric problems has been to subtract from all digital numbers (DN) the minimum pixel values of a dark object found in the scene. Often, however, there are no dark objects large enough to be identified. Again, an alternative is to use a pseudo invariant object (PIO) within the scene. PIO is a surface such as a parking lot or bare soil whose reflectance is known and remains constant over time. It is used to convert digital numbers into reflectance values and in this manner circumvent atmospheric effects. However, the reflectance properties do vary over time. Soil reflectance, for example, varies with moisture content and surface roughness which changes due to rainfall events. This invalidates the assumption of the invariant nature of such objects and results in uncertain conversions to reflectance values from which products such as fractional coverage are derived.

A physical property that does not vary with surface conditions is fractional green vegetation cover (fc). An object void of vegetation (OVV), such as soil, is located in the image. By definition, an OVV has 0% vegetative coverage. Atmospheric corrections can then be computed using the OVV in terms of vegetation cover. In this way, the bare soil as an OVV, is defined by numerically invariant properties, while the same bare soil, as a PIO, is defined in terms of reflectance properties which are variant (Qi et al., 2000). Each pixel normally contains a mixture of both soil and vegetation; the following "linear mixing" model of the resulting remote sensor signal, S, describes this relationship between the two physical characteristics where:

$$S = f_c S_v + (1 - f_c) S_s \qquad [5]$$

- fc = fractional green cover,
- 1- fc = fractional soil cover,

- Sv = vegetation reflectance,
- Ss = soil reflectance, and,
- S = the remote sensing signal.

In accordance with Qi et al. (2000), the NDVI was substituted for S in Equation 5 and algebraically rearranged to solve for fc where:

$$fc = (NDVI_{any} - NDVI_{soil})/(NDVI_{veg\max} - NDVI_{soil}) \qquad [6]$$

The vegetation maximum (veg max) indicates the highest vegetation NDVI from peak vegetation coverage. NDVI of the soil should be constant throughout the season and close to zero, but actually varies substantially with time and from location to location. Therefore, in their study, soil NDVI was calculated from the reflectance of each image. Qi et al. (2000) found that fc estimates agreed reasonably well with in situ measurements and seasonal trends of fc agreed reasonably well with field observations.

In the 2001 and 2002 field study, fractional canopy coverage (Eq. 6) of the carrot canopy was determined using NDVI derived from reflectance measurements taken throughout the two seasons and substituted for L in calculating SAVI, where L = (1-fc).

Materials and Methods

Experimental Sites, Plot Design, Management Protocol and Agronomic Sampling

Field studies were conducted at four locations during 2001 and 2002, in Montcalm County, Michigan. In both years plots were located at the Michigan State University Montcalm Experiment Station on moderately well drained loamy sand to sandy loam soil, of the Hillsdale-Spinks map unit (Hillsdale: coarse-loamy, mixed, mesic

Typic Hapludalfs, Spinks: sandy, mixed, mesic Psammentic Hapludalfs) (D.L. Mokma, personal communication, 2003). In both years Diamond Cut and Goliath varieties were planted on flat beds in early May and harvested in mid-September. Each year plots were also established on commercial carrot fields, at Sandyland Farms, on Plainfield Sand, including a loamy substratum at the 2001 site, (mixed mesic Typic Udipsamments) (D.L. Mokma, personal communication, 2003). Asgrow B1 and Prime Cut 59 varieties were planted at the 2001 site, and Sugar Snax 54 was planted at the 2002 site. The fields were planted in mid-April on raised beds and harvested in mid-August. Barley was planted between rows to protect emerging plants and killed off once the carrots were established. Four replications of each of four N-treatments, 45, 90, 135, 180 kg ha^{-1} were arranged in a randomized complete block design at all locations. Weeds were controlled with linuron, and foliar blight was controlled with chlorothalonil. A detailed description is given in the Materials and Methods section of Chapter 2.

Reflectance and Agronomic Measurements

Plant and soil reflectance measurements were made using a MSR87 multispectral radiometer (CropScan, Rochester, MN) equipped with the standard eight narrowband interference filters centered at 460, 510, 560, 610, 660, 710, 760, and 810 nm. Scanning direction was with the row, to minimize shadows by plants and the operator. The field of view was 28°, and measurements were viewed at nadir from a height of 2.55 m with a ground resolution diameter of 1.27 m. Additional information describing the equipment and the scanning protocol are given in the Materials and Methods section of Chapter 2. A Canon Powershot G1 digital camera was mounted alongside and at the same height as the radiometer at sampling. Digital images were taken of at least one scanned site per plot for a visual record of radiometric measurements. Ground resolution of the digital camera at a height of 2.55 m was 2.4 x 1.8 m. The images were used to determine percent vegetation coverage and verify the validity of the fc calculation as used in carrot.

Image Processing

Digital images were cropped to match the area viewed by the radiometer with an image processing application (PhotoImpact 7, Ulead, Taipei, Taiwan). Using the image pixel count, a circle was generated from the image center outward, equal in size to the diameter of the ground resolution of the radiometer. The supervised classification tools of Erdas Imagine 8.5 were used to redefine the pixels of the cropped image into soil and vegetation. Polygons, representative of the various elements of the image, were drawn and assigned signature definitions. The classification process then tested the definitions against each pixel in the image using maximum likelihood parameters to reclassify and recolor the pixels under these new definitions. This process made it possible to quantify the number of pixels attributed to soil and vegetation. The percent coverage was derived from the pixel count defined as vegetation. It was necessary to develop two signature files, one file covering the Montcalm Experiment Station in 2001 and 2002 with eight signature definitions, the other file covering the Sandyland location in 2001 and 2002 with nine signature definitions. Each signature file was used in the classification process of the appropriate group of images. The classified images were used to verify the accuracy of the fc calculation.

The *fc* Calculation

Fractional cover (*fc*) was calculated according to Eq. 6. NDVI for each plot was calculated from the averaged NIR waveband centered at 810 nm, and red waveband centered at 660 nm according to Eq. 3. In applying Eq. 6, $NDVI_{soil}$ for the Montcalm Experiment Station in 2001 was derived from one set of soil reflectance measurements taken on May 18. Since the Sandyland location in 2001 was already established when plots were staked and a large enough area of bare soil was no longer available, the Experiment Station soil data was used in the model for Sandyland as an OVV, object void of vegetation. Soils from the two locations were similar in color, organic matter content, and water holding capacity. $NDVI_{soil}$ for both the Montcalm Experiment Station and the Sandyland location in 2002 was derived from on-site bare soil measurements taken throughout the season. $NDVI_{veg\ max}$ was derived from the seasonal peak canopy reflectance measurements obtained from each location. Linear regression was used to evaluate the relationship between percent vegetation coverage determined from the classified images, and *fc* calculated from Eq. 6 according to multiple regression and general linear models (SAS Inst. Inc., Release 8.2/2003).

Results and Discussion

All data were normally distributed as evidenced by the Shapiro-Wilk test and residual plots. An outlier was defined as a viewing combination in which the camera and radiometer viewed different amounts of vegatation coverage as a result of gaps due to incomplete canopy coverage across the bed. Approximately 650 measurements were tested, and 12 were removed as outliers.

In 2001, reflectance measurements at the experiment station began with plant emergence and showed that at about 45 days following planting, the plant canopy was large enough to produce a usable comparison between the percent foliar coverage derived from the classified digital images and the calculated fc; ($r^2 = 0.54$). Measurements taken earlier resulted in coverage values so small that they were effectively zero. From days 51 and 54 to mid-July, fc (Eq. 6) correlated well with the amount of canopy coverage derived from digital images, with $r^2 = 0.69 - 0.91$ at both locations (Table 1). As the canopy reached closure, correlation between the two parameters varied. At the Experiment Station, correlation appeared to diminish at about 86 days of development when canopy coverage ranged from 87 to 96%, according to the classified digital images. In contrast, at Sandyland correlation with fc lasted until the carrot crop was 91 days old, at which time canopy closure was at 99%. The successful Sandyland results also indicated that the Experiment Station soil reflectance could be used as an object void of vegetation (OVV) in the Sandyland data for the sole purpose of calculating fc.

During the 2002 season (Table 2) reflectance measurements were delayed until later in the season and continued beyond peak canopy closure until harvest, since early measurements in 2001 resulted in effectively zero coverage values. Most of the measurements were taken during the last 45 days before harvest, over canopies with 90 to 99% closure, according to the classified digital images, and also revealed that once the canopy reached peak closure, the correlation with fc diminished. This was especially notable in the Goliath data. On July 17 and 24, fc correlated with percent vegetation coverage with $r^2 = 0.80$ and 0.82, but dropped sharply thereafter.

In 2002 at Sandyland, data collection was interupted by a number of sensor

Table 1. 2001 Regression analysis of Percent Vegetation Coverage (PVC) vs Calculated fc (PVC = a + bfc +cTreatment) where a is the intercept and b and c are regression coefficients. Treatment did not significantly influence correlation of PVC with fc at $p < 0.05$.

Date	DAP†	y Intercept	fc Coefficient (b)	r^2	p-value
		Montcalm Experiment Station			
5/18/01	10	0	0	0	0
6/13/01	36	0	0	0	0
6/22/01	45	-0.0194	0.9657	0.54	.0012
6/28/01	51	-0.0157	1.1561	0.78	<.0001
7/5/01	58	-0.0897	1.2464	0.89	<.0001
7/12/01	65	-0.0751	1.0856	0.73	<.0001
7/20/01	73	-0.1038	1.0933	0.91	<.0001
8/2/01	86	0.0945	0.8903	0.60	.0004
8/9/01	93	-0.0565	1.0518	0.68	<.0001
8/17/01	101	-1.1406	2.1257	0.39	.0091
		Sandyland (Deaner Rd)			
6/13/01	54	0.0671	0.8485	0.75	<.0001
6/22/01	63	0.0427	0.7893	0.69	<.0001
6/28/01	69	-0.0643	1.0200	0.88	<.0001
7/5/01	76	-0.3450	1.3534	0.88	<.0001
7/12/01	83	-1.0679	2.1098	0.78	<.0001
7/19/01	91	-1.2507	2.2358	0.78	<.0001
8/9/01	111	0	0	0	0
8/17/01	119	0.9041	0.0902	0.04	.4500

†Days after planting

equipment mishaps resulting in only three successful sampling dates. On August 9 and 15, the canopy was at full coverage and also exhibited the same late-season lack of correlation between the percent canopy coverage derived from digital images and fc.

A full canopy, whether defined by fc or percent vegetation coverage derived from classified digital images, is equal to 1.0, with the linear regression model resulting in zero or at least very low correlation due to clustering of points. Tables 1 and 2 indicate a late season drop in correlation at all four locations; however, the time at which the clustering appeared varied between the locations. Population and varietal differences such as leaf

Table 2. 2002 Regression analysis of Percent Vegetation Coverage (PVC) vs. Calculated *f*c (PVC = a + b*f*c + cTreatment) where a is the intercept and b and c are regression coefficients. Treatment significantly influenced correlation of PVC with *f*c on the dates indicated at $p < 0.05$.

Date	DAP†	y Intercept	*f*c Coefficient (b)	Trt Coefficient (c)	r^2	p-value
			Montcalm Experiment Station Diamond Cut			
5/21/02	14	0	0	0	0	0
7/17/02	71	0.2325	0.7450	-0.0006	0.66	.0008
7/24/02	78	0.3467	0.6432		0.45	.0040
8/1/02	86	0.8221	0.1634	-0.0043‡	0.39	.0400
8/9/02	94	0.6757	0.2852		0.27	.0400
8/15/02	100	0.7867	0.2119	-0.0001	0.70	.0014
8/21/02	106	0.3912	0.6151	-0.0001	0.54	.0066
8/30/02	115	0.4771	0.4281		.11	.2100
9/6/02	122	0.0732	0.9615	-0.0002	.74	.0003
			Montcalm Experiment Station Goliath			
5/21/02	14	0	0	0	0	0
7/17/02	71	-0.1192	1.1238		0.80	<.0001
7/24/02	78	0.0242	0.9565		0.82	<.0001
8/1/02	86	0.5801	0.4052		0.62	.0003
8/9/02	94	0.5372	0.4161		0.40	.0089
8/15/02	100	0.4414	0.5360		0.44	.0048
8/21/02	106	-0.3951	1.4147	-0.0003	.64	.0010
8/30/02	115	0.7422	0.1372		.005	.8000
9/6/02	122	0.9102	-0.0098		.0001	.9680
			Sandyland (Masters Rd)			
7/24/02	89	0.3606	0.5869		0.30	.0300
8/9/02	105	0.3016	0.6766		0.22	.0700
8/15/02	111	0.9214	0.0695		0.04	.4700

† Days after planting
‡ p-value 0.08

orientation, leaf size, canopy fullness, and developmental rate can contribute to timing of full canopy. Differences in late season results may have been affected, in part, by the manner in which the digital images were classified. Shadows that represented either small pockets of soil or shaded leaves nestled in the canopy were difficult to distinguish in the images. The shadows, which also represented a decrease in light spectra, affected the resulting reflectance measurements. Incorrect interpretation of the shadows in the digital images undoubtedly influenced the correlation of the images versus *f*c.

In 2002, the Goliath variety, at the Experiment Station, was affected by foliar blight. The canopy coverage was reduced during the latter part of the season and it was expected that the percent coverage derived from classified digital images versus *f*c would return to a more linear relationship; however, that was not the outcome (Table 2). In addition to the shadows, leaf discoloration also made interpretation of the digital images in relation to the reflectance measurements difficult.

N treatments did not significantly influence the percent canopy coverage in 2001 (data not shown) according to multiple linear regression. However, on three occasions at the experiment station, certain treatments differed significantly or nearly significantly at $p \leq 0.05$, but did not necessarily vary sequentially (Table 3). On three occasions at Sandyland, treatment differences were notable but not significant and percent vegetation coverage was not significantly influenced by treatment.

During 2002, multiple linear regression, comparing percent vegetation coverage to *f*c and treatments, showed that treatment significantly influenced the percent canopy coverage derived from digital images in the Diamond Cut variety on four occasions July 17, August 15, August 21, and September 6 (Table 2). Table 3 indicates significant differences at $p \leq 0.05$, but treatments significantly influenced percent vegetation coverage on less than half of the sampling dates shown; not necessarily sequentially. In the Goliath variety Table 2 shows that treatment was significant only on August 21, but only on September 6 was there significant separation of treatments according to the general linear model.

Lack of signficant correlation between canopy coverage derived from the images and the fc calculation versus treatments was not unexpected. The typical density of carrot planting and thickness of the maturing canopy may dilute the distinction between treatments where biomass differences may be nonexistent. Overall, fc determined from NIR and red reflectance measurements correlated reasonably well with percent vegetative coverage derived from digital images throughout most of the season. Earliest correlation

Table 3. Mean Percent Vegetation Coverage as influence by fc and treatment differences on selected dates.

Montcalm Experiment Station 2001				Sandyland (Deaner Rd) 2001			
trt	July 5	July 12	Aug 9	trt	July 5	July 12	July 20
kg ha^{-1}	--Percent Canopy Coverage----			kg ha^{-1}	--Percent Canopy Coverage----		
45	21a	39a	98a	45	74b	88b	92b
90	18a	33a	97a	90	76ab	90a	95a
135	19a	33a	96a	135	82a	90ab	95a
180	19a	33a	98a	180	70b	88ab	93a
$p^{\dagger}$	.004	.014	.115	$p^{\dagger}$	.375	.741	.430

Montcalm Experiment Station (Diamond Cut) 2002						
trt	July 17‡	Aug 1	Aug 9	Aug 15‡	Aug 21‡	Sept 6‡
kg ha^{-1}	--------------------------------Percent Canopy Coverage----------------------------					
45	72a	97a	95a	99a	97a	93a
90	71a	96ab	93a	99a	97a	94a
135	67a	95b	94a	98ab	97a	93a
180	64a	96ab	95a	98b	96a	94a
$p^{\dagger}$	.146	.026	.039	.009	.151	.047

Montcalm Experiment Station (Goliath) 2002					
trt	July 17	July 24	Aug 9	Aug 21‡	Sept 6
kg ha^{-1}	--------------------------------Percent Canopy Coverage----------------------------				
45	64ab	80ab	93a	97a	92a
90	72a	85a	92a	92a	88b
135	57b	75b	94a	94a	91ab
180	69a	81ab	94a	93a	89ab
$p^{\dagger}$	.274	.286	.399	.110	.017

Mean values with the same letter are not significantly different at $p < 0.05$.

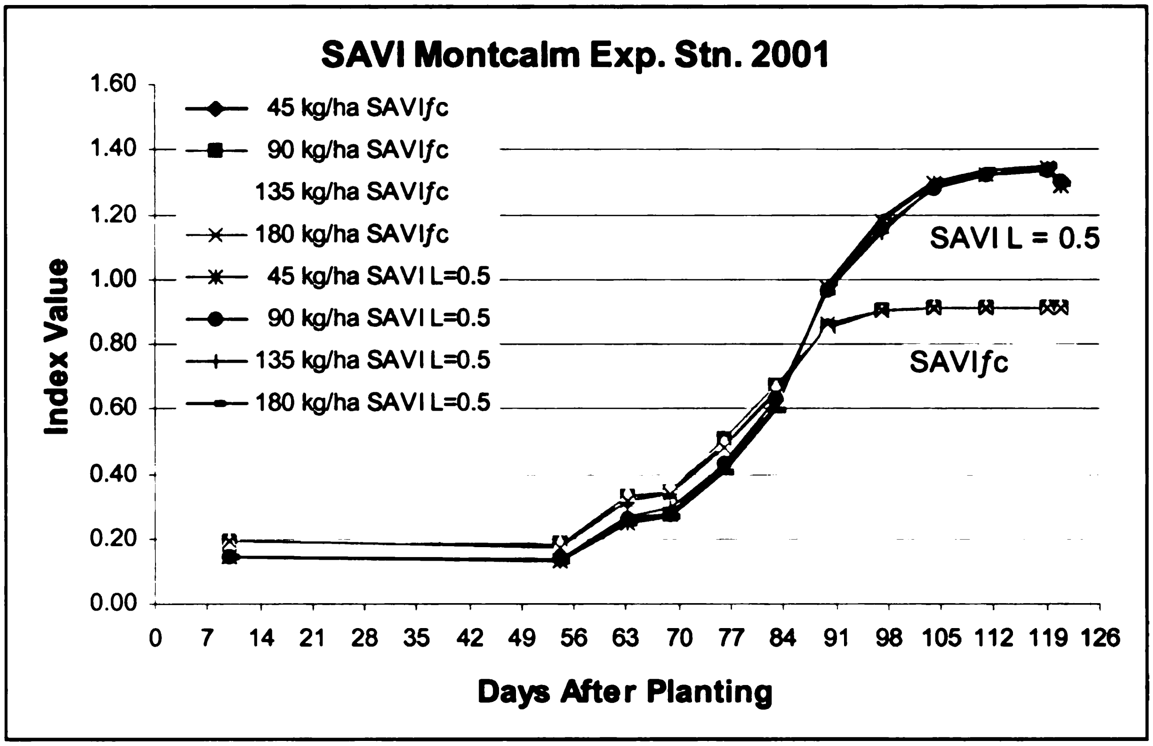
† p = p-value of overall treatment response according to the analysis of variance.

‡ Treatment response significantly influenced correlation of percent canopy coverage with fc according to regression analysis on these dates. (See Table 2).

was possible at about 45 days at the experiment station in 2001. Other varieties may vary according to growth patterns and climate. Saturation of fc occurred at peak canopy coverage when fc = 1.0. L, the soil adjustment factor of SAVI, is defined as zero at full coverage and therefore (1-fc) satisfies the soil adjustment factor at saturation.

SAVI was derived for all reflectance measurements using fc as the soil adjustment factor L = (1-fc) to determine whether it improved the accuracy of the vegetation index. For comparison, L was also held constant at 0.5 as is typically done when the amount of coverage is unknown (US Water Conservation Laboratory, 2003). Rondeaux et al. (1995) and Gao et al. (2000) also used L = 0.5 as a basis for their comparative model testing. When L was held constant at 0.5, treatment differences remained separated and resembled the growth curve, however, the index exceeded its expected range when canopy coverage was dense. When L = (1-fc) was substituted, SAVI was held to its dynamic range of -1.0 to 1.0, the curves then plateaued at peak canopy coverage and treatment differences were no longer distinguishable. Figures 1 through 3 depict the comparison between L = 0.5 and L = (1-fc).

SAVI, where L = (1- fc) [SAVIfc], was also derived for all reflectance measurements without the multiplier (1+L) as Rondeaux et al. (1995) had done. The resulting curves plotted over time were within the expected range for SAVI and resembled the growth curve. Without the multiplier, SAVIfc did not plateau at peak canopy, and the treatment effect remained separated. Figure 4 is an example taken from the Diamond Cut variety, Experiment Station, 2002 with and without the multiplier (1+(1-fc)). The data from the other locations exhibited similar differences. Without the multiplier (1+L), SAVIfc did not measurably change the outcome of SAVI in the carrot



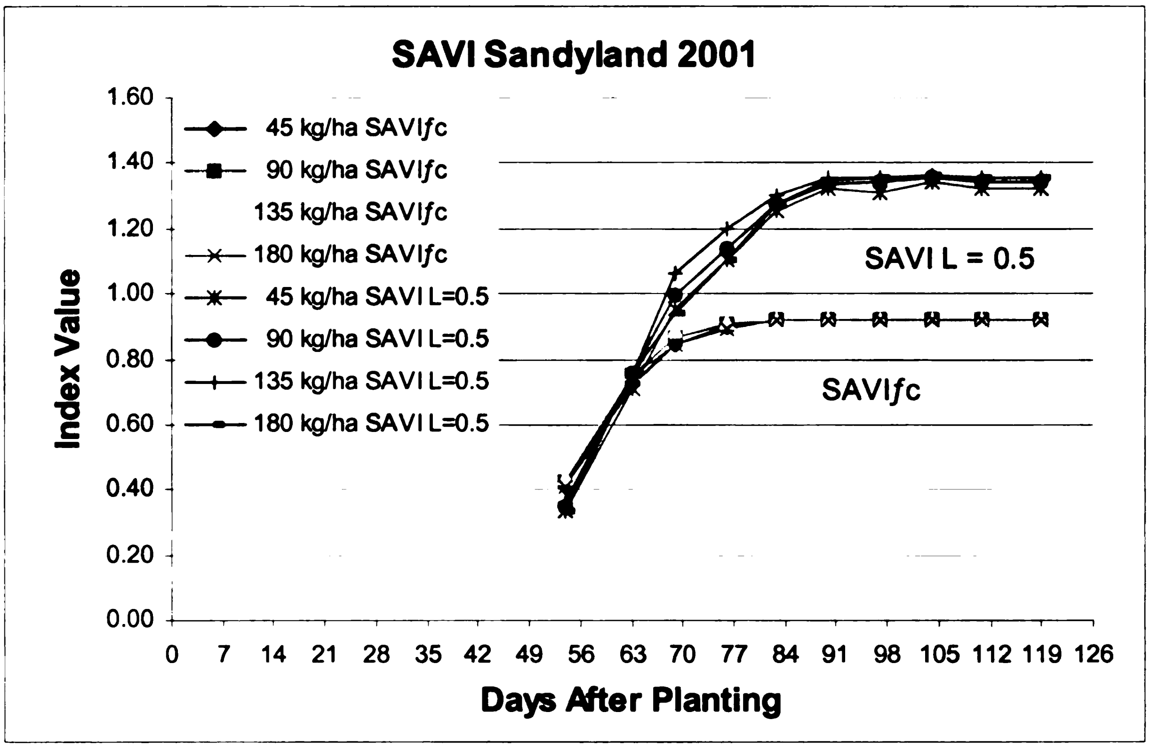
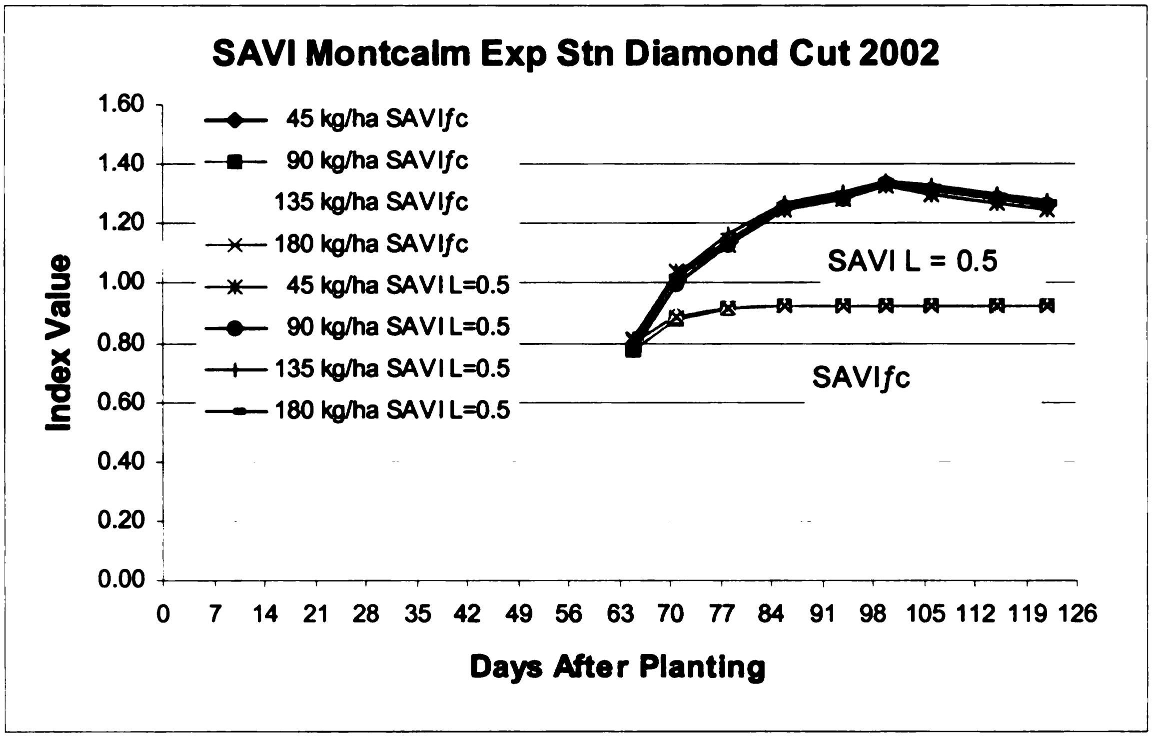


Fig. 1 Results of SAVI*fc* and SAVI L = 0.5 for the 2001 field season at the Montcalm Experiment Station and Sandyland locations.
Images in this thesis are presented in color.



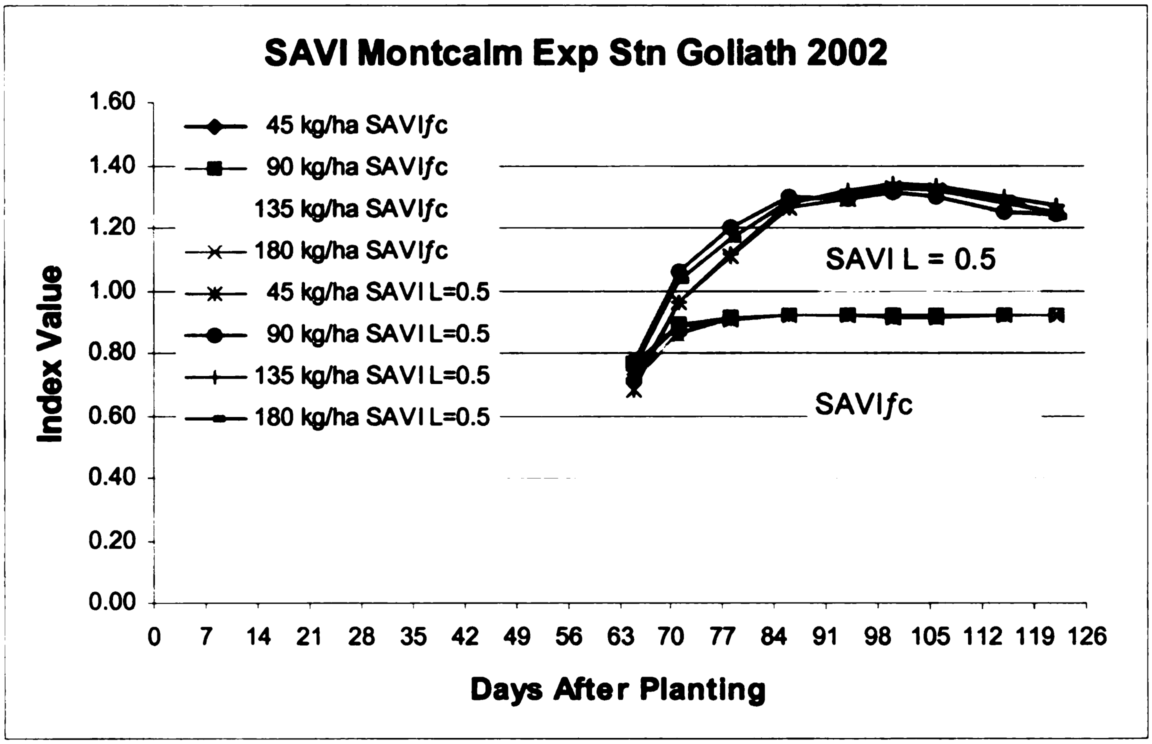


Fig. 2 Results of SAVI*fc* and SAVI L = 0.5 for the Diamond Cut and Goliath varieties at the Montcalm Experiment Station for the 2002 field season.
Images in this thesis are presented in color.

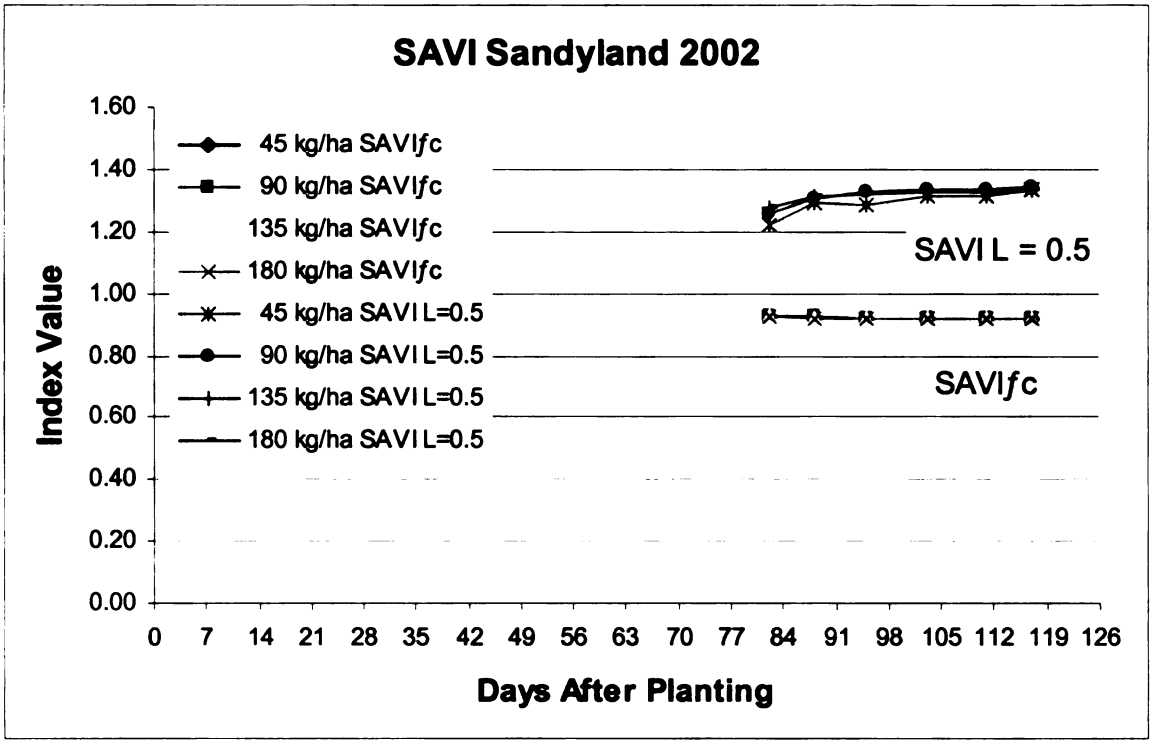


Fig. 3 Results of SAVI*f*c and SAVI L = 0.5 at Sandyland for the 2002 field season. Images in this thesis are presented in color.

crop. In fact, regression analysis (Table 4) revealed a significant relationship; (r^2 = 0.99 to 1.0) for every date throughout the growing season at all four locations.

Differences between SAVI and SAVI*f*c were expected to occur during early and late developmental stages of the carrot crop when the canopy coverage, and therefore *f*c, differed from the previously defined L = 0.5. Figures 1 through 3 show that SAVI*f*c preserved the dynamic range of SAVI even in dense canopy coverage, while L held constant at 0.5 exceeded the expected range by as much as 30%. In addition, the curves crossed each other at the point where L = 0.5 under both definitions of L, as expected, approximately 63 to 65 days after planting (Table 3) at about 50% canopy coverage (Figures 1 through 3). Where L was held constant, SAVI, while a reasonable estimation

(US Water Conservation Laboratory), was understated in low canopy coverage and overstated in dense canopy conditions compared to SAVIfc.

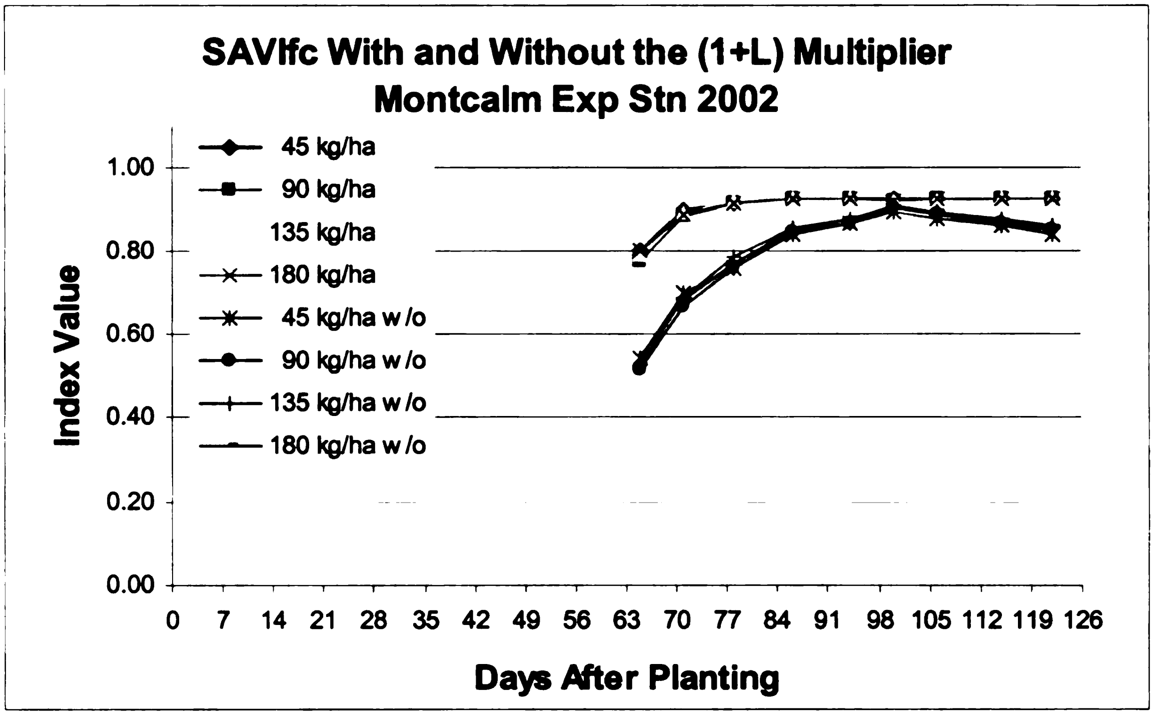


Fig. 4 Example of the difference between SAVIfc with and without the (1+L) multiplier. The Experiment Station 2002, Diamond Cut data is shown here, the other locations exhibited similar differences.
Images in this thesis are presented in color.

Conclusion

Images were used to assess the reliability of fc (Eq. 6) in estimating canopy coverage. As the canopy neared closure fc tended to saturate. Late season images presented challenges to the interpretation of the shadows created by the sun angle reflecting off soil, shaded leaves, and leaf discoloration. Despite this, fc could be used to predict percent vegetation coverage. When fc was used as the soil adjustment factor L = (1-fc) to calculate SAVI, it was determined that for the carrot studies in 2001 and 2002, L = (1-*f*c) held SAVI to its dynamic range of -1.0 to 1.0 even when the canopy was dense. However, differences between treatments were best viewed when SAVI*f*c was determined without the multiplier (1+L) in Equation 6.

Table 4. Results of regression analysis of SAVI comparing L = 0.5 and L = (1-*f*c).

Date	Days†	Average 1-*f*c‡	r^2	Date	Days†	Average 1-*f*c‡	r^2
Montcalm Exp Stn				Sandyland (Deaner Rd)			
5/18/01	10	1.00	1.00***				
6/13/01	36	1.00	1.00***	6/13/01	54	0.84	1.00***
6/22/01	45	0.91	1.00***	6/22/01	63	0.51	1.00***
6/28/01	51	0.89	1.00***	6/28/01	69	0.31	1.00***
7/5/01	58	0.77	1.00***	7/5/01	76	0.19	1.00***
7/12/01	65	0.61	1.00***	7/12/01	83	0.07	0.99***
7/20/01	73	0.32	1.00***	7/20/01	91	0.02	0.99***
7/26/01	79	0.15	1.00***	7/26/01	97	0.02	0.99***
8/2/01	86	0.05	0.99***	8/2/01	104	0.01	0.99***
8/9/01	93	0.03	0.99***	8/09/01	111	0.02	0.99***
8/17/01	101	0.01	0.99***	8/17/01	119	0.02	0.99***
9/6/01	121	0.05	0.99***				
Montcalm Exp Stn, Diamond Cut				Montcalm Exp Stn, Goliath			
5/21/02	14	1.00	1.00***	5/21/02	14	1.00	1.00***
7/11/02	65	0.49	1.00***	7/11/02	65	0.54	1.00***
7/17/02	71	0.31	1.00***	7/17/02	71	0.31	1.00***
7/24/02	78	0.20	0.99***	7/24/02	78	0.18	1.00***
8/1/02	86	0.09	0.99***	8/1/02	86	0.07	0.99***
8/9/02	94	0.06	0.99***	8/9/02	94	0.05	0.99***
8/15/02	100	0.02	0.99***	8/15/02	100	0.02	0.99***
8/21/02	106	0.04	0.99***	8/21/02	106	0.03	0.99***
8/30/02	115	0.07	0.99***	8/30/02	115	0.06	0.99***
9/6/02	122	0.09	0.99***	9/6/02	122	0.09	0.99***
Sandyland (Masters Rd)							
7/11/02	71	0.09	0.99***				
7/17/02	82	0.05	0.99***				
7/24/02	89	0.04	0.99***				
8/1/02	97	0.03	0.99***				
8/9/02	105	0.03	0.99***				
8/15/02	111	0.02	0.99***				

† Days means number of days since planting.
‡ All treatments were combined to show general coverage at the specified days after planting.
*** p-value <.0001

The choice of L in SAVI-type indices, while critical in minimizing the soil background effect (Rondeaux et al., 1995), should also be simple to apply, especially if these indices will become integral to production agriculture. fc is easy to apply as the definition of the soil background adjustment factor because it is obtained from reflectance measurements, which would already be available.

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