ESTIMATING NITROGEN FERTILIZER REQUIREMENTS OF CANOLA (*BRASSICA NAPUS* L.) USING SENSOR-BASED ESTIMATES OF YIELD POTENTIAL AND CROP RESPONSE TO NITROGEN

BY

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ABSTRACT

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<u>Estimating nitrogen fertilizer requirements of canola (*Brassica napus* L.) using sensor-based estimates of yield potential and crop response to nitrogen</u>. Major Professors; Dr. Paul Bullock and Dr. Guy Lafond. The challenge in managing nitrogen (N) fertilizer in canola (*Brassica napus* L.) production is deciding on application rates that meet but do not exceed the demands of the crop for its specific environment. Crop N requirements depend on their potential yield, the extent of N losses, and the soil's capacity to supply N to the crop; all of which are difficult to quantify and highly variable. Active optical sensors have potential to improve upon our ability to match N inputs with crop demands. We completed several field experiments with canola at various locations in 2005 and 2006 to establish whether current sensing technology and application equipment can be adapted to improve upon our current ability to manage N fertilizer in canola production.

First, we determined whether it was possible to estimate the potential yield of canola using normalized difference vegetation index (NDVI) measurements and the best methods for doing so. We established field experiments with canola where we varied N fertilizer and seeding rates at Brandon, Indian Head, Ottawa, Scott, and Swift Current to achieve a wide range of grain yields. The correlation between NDVI and yield generally remained weak until the canola had five leaves, at which point it improved until peaking at the mid to late-bolting stage and generally became very weak when the canola was in full bloom. When the data from selected sites and sensing dates were compiled, a reasonably strong exponential relationship existed between NDVI and grain yield (R^2 =

0.444). While the best relationship was obtained when we divided NDVI by corn heat units (R^2=0.562), all the heat units tested performed similarly and dividing NDVI by days from planting was also reasonably effective (R^2=0.474).

Our next objective was to assess the potential benefits and risks of fine-tuning post-emergent N rates using optical sensors relative to the predominant practice of applying the crop's entire N requirements at seeding. In plot studies at Indian Head and Scott, SK, we evaluated several N management treatments with respect to N fertilizer use (kg N ha^{-1}), canola seed yield (kg ha^{-1}), and agronomic N use efficiency (kg grain kg N applied^{-1}). While we always reduced N use using NDVI measurement to fine-tune N rates in the small plot studies, doing so resulted in substantial yield losses at Indian Head in 2006, where it was very hot and dry late in the season. Agronomic N use-efficiency (ANUE) was increased using the sensor at one site-year and was never lower than in the benchmark treatment. The results were similar in nine large-scale trials with commercial equipment that we completed in cooperation with producers. In most of the on-farm trials, we reduced N fertilizer with no impact on yield, thus likely increasing N use-efficiency in several cases. However, the dollar value of the savings in fertilizer N rarely exceeded the cost of the post-emergent (PE) N application and marginal economic returns for the two treatments were usually similar.

Sensor-based N management appears to be a feasible option for canola production in western Canada and has potential to increase N use-efficiency over the long-term. However, increased efficiency alone will not provide sufficient motivation for producers to adopt this technology and whether or not sensor-based N management is economically advantageous over current practices remains uncertain.

APPROVAL AND COPYRIGHT FORMS

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FOREWORD

The research presented in this thesis represents only a few aspects of a much broader project with which I am currently involved. This project is a joint effort by

IHARF and AAFC and involves the development and evaluation of sensor-based N application algorithms for canola, spring wheat, durum, winter wheat, barley, and oats under western Canadian growing conditions. Field experiments are being conducted at AAFC locations at Indian Head, Scott, Swift Current, Brandon, and Ottawa. To compliment this work, we are also conducting experiments to quantify NH_3 and N_2O emissions from urea applied at seeding versus post-emergent, surface-applied urea-ammonium nitrate (UAN).

While we plan to publish variations of chapters 3, 4, and 5 in peer-reviewed journals, all field experiments discussed in this thesis were continued at all of the locations in the 2007 growing season. Consequently, we will not be publishing any of the material presented in this thesis until the 2007 data has been included.

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1. AAFC – Agriculture and Agri-Food Canada
2. ANUE – Agronomic Nitrogen Use-Efficiency
3. CHU – Corn Heat Units
4. CRD – Completely Randomized Design
5. EMR – Electromagnetic Radiation
6. FP – Farmer Practice
7. GDD – Growing Degree Days
8. GLM – General Linear Model
9. GPS – Global Positioning System
10. IHARF – Indian Head Agricultural Research Foundation
11. IHRF – Indian Head Research Farm
12. IRVI – Inverse Rate Vegetation Index
13. MAP – Mono-Ammonium Phosphate
14. MIT – Mineralization-Immobilization Turnover
15. MSAVI –Modified Soil Adjusted Vegetation Index
16. NBPT – N-(*n*-butyl) thiophosphoric triamide ()
17. NDVI – Normalized Difference Vegetation Index
18. NIR – Near Infrared
19. NR – Nitrogen Rich
20. NUE – Nitrogen Use-Efficiency
21. OSU – Oklahoma State University
22. P-Days – Physiological Days
23. PE – Post-Emergent
24. RCBD – Randomized Complete Block Design
25. RI – Response Index
26. RN – Reduced Nitrogen
27. RVI – Ratio Vegetation Index
28. SAVI – Soil Adjusted Vegetation Index
29. SDB – Surface Dribble-Band
30. SOM – Soil Organic Matter
31. SF – Split-Application / Fixed Rate
32. TSAVI – Transformed Soil Adjusted Vegetation Index
33. UAN – urea ammonium nitrate
34. VI – Vegetation Index
35. VRA – Variable Rate Application
36. WDVI – Weighted Difference Vegetation Index
37. WDRVI – Wide Dynamic Range Vegetation Index
38. WUE – Water Use-Efficiency
39. YP – Yield Potential

1.0 INTRODUCTION

Producers in the Canadian prairies apply more nitrogen (N) as fertilizer than any other nutrient and, assuming a fertilizer price of \$0.90 kg N^{-1}, the value of the N applied in Canada exceeds \$1.4 billion each year (Korol 2002; based on 2002 retail sales). Of the N fertilizer that is applied, however, crops typically utilize less than 50% in the year of application and approximately 65% over a period of five growing seasons (Krupnik et al. 2002). Because the efficiency of N fertilizer decreases rapidly as rates begin to exceed crop requirements (Johnston et al. 1997; Chamorro et al. 2002), producers should ideally apply only as much N as the crop can utilize, thus minimizing the potential for losses and maximizing economic returns. However, limitations in our ability to estimate crop N requirements, potential losses of N, and the soil's capacity to supply N make decisions regarding N fertilizer rates difficult.

Recent developments in optical sensing technology and innovative approaches to using this technology are showing potential to improve our ability to assess the N status of crops and fine-tune N rates. The GreenSeeker^{TM} (NTech Industries) is an example of a ground-based, active optical sensing system that has several advantages over more traditional satellite-mounted, passive sensors, perhaps most importantly their ability to integrate with fertilizer application equipment and be used as a basis for prescribing and applying variable rates of post-emergent N in real time.

A key advantage to managing N using optical sensors is their ability to estimate the potential yields of crops in their current, specific environment during the growing season. The most widely used index calculated by sensors like the GreenSeeker^{TM} is the normalized difference vegetation index (NDVI), which is correlated with a variety of canopy characteristics including above ground biomass and total N-uptake (Moges et al. 2004; Freeman et al. 2007). However, NDVI on its own is simply a numerical value that has been shown to increase with increasing biomass (Tucker and Sellers 1986), therefore previously established relationships between observed NDVI values and crop measurements are required to use this index to quantitatively estimate crop parameters. Raun et al. (2002) advocated a method for estimating grain yields of winter wheat using optical sensors whereby they divided NDVI by the number of days between planting and sensing and established the correlation between the quotient and grain yield. Dividing NDVI by days reduced the effects of crop growth on NDVI values collected on different days, thus increasing the range of growth stages during which the technology could be applied (Raun et al. 2002). For corn, Teal et al. (2006) found that dividing NDVI by growing degree-days accumulated between seeding and sensing further increased the range of growth stages where yields could be estimated compared with dividing by the number of days from planting. Despite this crop's relatively high N requirements and economic importance, such empirical relationships have not yet been developed for canola (*Brassica napus* L.).

An important component to estimating N fertilizer requirements using optical sensors is to determine the crop's potential response to additional inputs of N. Raun et al. (2002) achieved this by establishing reference areas in the field that were not limited by N and comparing the crop growing in the reference area to that in adjacent areas of the field later on in the growing season, (Raun et al. 2002). Mullen et al. (2003) provided further validation for this approach when they showed that the ratio of NDVI measurements of winter wheat growing in contrasting N fertility environments and that of the observed grain yields in the same two environments are linearly related to one another (R^2=0.56). It follows that if we can use optical sensors to estimate both the potential yields of crops along with their potential responsiveness to additional N inputs, then we can use the sensors as a means of objectively estimating additional post-emergent (PE) crop N requirements. In this manner, Raun et al. (2002) increased net revenues and fertilizer N use-efficiency for winter wheat production by either maintaining yields with less fertilizer N or by increasing grain yields with post-emergent N when there was opportunity to do so.

The objectives of this study were to establish whether active optical sensors and the existing methods of using these sensors could be adapted to improve our ability to match N rates with crop requirements and increase the efficiency of N fertilizer in canola production relative to more conventional N management practices. For Canadian producers to adopt this technology and use it in an effective manner, a number of conditions must be satisfied. First, it must be established that in-season NDVI measurements can be used to estimate canola yield potential early enough for N deficiencies to be corrected. Ideally, the empirical relationships between NDVI and yield should be adaptable over the wide range of environmental conditions that exist in Canadian agroecosystems and would account for factors other than N availability that can affect canola yields prior to sensing. Second, sensor-based approaches to managing N must be measurably beneficial over current practices in terms of N use-efficiency and, for producers to justify adopting the technology, profitability. Finally, for widespread adoption of sensor-based N management on a production scale to occur, implementation must be feasible using currently available application equipment, without being overly complicated or subjecting producers to an unacceptable amount of risk.

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2.0 REVIEW OF THE LITERATURE

2.1 INTRODUCTION

Nitrogen (N) is the most commonly limiting nutrient in the production of non-N-fixing crops (Havlin et al. 2005) and as such, producers apply more N as fertilizer than any other nutrient (Table 1; Korol 2002). In 2001/2002 (year ended June 30, 2002), over 1.5 million tones of inorganic N were purchased in Canada, with the Prairies (including northern British Columbia) accounting for more than 80% of the sales (Korol 2002). Urea and anhydrous ammonia are the dominant forms applied; together accounting for 72% of total N sales and ammonium sulphate, ammonium nitrate, monoammonium phosphate (MAP), and urea ammonium nitrate are also important sources of N fertilizer.

Table 2.1. Canadian consumption of commercial fertilizer in 2001/2002 (year-end June 30, 2002) (adapted from Korol 2002).

		Nutrient Content		
Fertilizer Type	**Quantity**	**Nitrogen** (N)	**Phosphate** (P_2O_5)	**Potash** (K_20)
	(tonnes)			
Urea	1 464 120	673 495		
Ammonium Sulphate	363 004	76 231		
Ammonium Nitrate	267 702	91 019		
Anhydrous Ammonia	546 767	448 349		
Nitrogen Solutions	372 128	87 049		
Calcium Ammonium Nitrate	77 824	21 124		
Monoammonium Phosphate	1 020 262	111 880	522 685	
Diammonium Phosphate	135 188	24 334	62 186	
Ammonium Polyphosphate	75 352	7 535	25 620	
Other[z]	703 359	14 944	19 925	324 307
Total	**5 025 706**	**1 555 960**	**630 416**	**324 307**

[z] Includes all other commercial fertilizer types, regardless of whether or not they contain N

Assuming a fertilizer price of \$0.90 kg N^{-1}, the value of the synthetic N consumed in Canada exceeds 1.4 billion dollars. As with any openly traded commodity, the price of N fertilizer fluctuates in both directions over the short-term. However, because of the increasing human population and the high-energy demands of manufacturing N fertilizer, it is highly probable that the price of N fertilizers will continue to increase in the long-term. Furthermore, improper use of N fertilizer and application rates that are excessive increase the risk of environmental degradation. As such, using N fertilizers as efficiently as possible is imperative for crop production in the Canadian Prairies to be economically and environmentally sustainable.

Plants take in N as either nitrate (NO_3^-) or ammonium (NH_4^+) and generally grow best when both forms are available (Cramer and Lewis 1993). Plants convert most of the N that they consume into amino acids, proteins and nucleic acids and typically contain 1 – 6% N by weight (Campbell and Reece 2002; Havlin et al. 2005). Nitrogen is also an essential ingredient in the chemical structure of chlorophyll, the molecule responsible for converting light into the chemical energy that drives photosynthesis (Havlin et al. 2005). Thus, applications of fertilizer N are often well justified, as plants cannot function in the absence of this essential nutrient.

While N is important for all crops, wherever possible this review focuses on canola (*Brassica napus* L.), a crop which has its genetic roots as an ancient oilseed crop known as rapeseed. Originally used as a fuel source for lamps, industrial use of rapeseed oil did not flourish until the development of steam power when rapeseed oil gained a reputation as one of the best lubricants of its time. Rapeseed oil began to be recognized as a potential food source by the end of World War II if processing techniques could be improved. Further deterrents to rapeseed as a food source were the high eicosenoic and erucic acid contents of its oil, while livestock nutritionists had concerns about the sharp tasting and anti-nutritive glucosinolates (the compounds that give mustard its sharp taste), contained in the protein meal. In 1974 at the University of Manitoba, Dr. Baldur Stefansson bred a variety of rapeseed, c.v. Tower, which had reduced levels of both erucic acid and glucosinolate. Tower, a *napus* variety, was the first cultivar of rapeseed to meet the requirements of a new, improved crop that would become known as canola (Canola Council of Canada 2005a). By definition, canola is a plant that produces:

> "an oil that must contain less than two percent erucic acid, and the solid component of the seed must contain less than 30 micromoles of any one or any mixture of 3-betenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3 butenyl glucosinolate, and 2-hydroxy-4-pentenyl glucosinolate per gram of air-dry, oil-free solid (Canola Council of Canada 2005a)."

Though once considered a specialty crop, canola has developed into one of Canada's most economically important crops, rivalling wheat (*Triticum aestivum* L.) in terms of gross revenue (Food and Agriculture Organization of the United Nations 2006). In 2004, the Canadian acreage of canola and mustard (*Brassica juncea* L.) exceeded 8 million ha and production exceeded 8 million Mt of grain (Food and Agriculture Organization of the United Nations 2006).

2.2 CANOLA RESPONSE TO NITROGEN FERTILITY

Under N limiting conditions, canola responds to increased N fertility in a variety of ways. The economic viability of N fertilizer applications depends on the potential crop responses and the opportunities for producers to capitalize upon them. For instance, high N rates often elevate protein levels in canola, sometimes at the expense of oil content (Jackson 2000; Malhi and Gill 2004). However, because producers are paid on a weight basis with no penalties for low oil content or premiums for high oil content, it makes sense for them to apply N as long as doing so increases grain yield sufficiently to pay for the added fertilizer, regardless of the effects on oil content. Similarly, increases in straw production with no effects on grain yield are of no immediate economic value to producers if they are selling only the grain.

One of the earliest detectable crop responses to increasing N fertility is increased N uptake. Increases in N uptake can result from N becoming more concentrated in the plant tissues (Chamorro et al. 2002), increased dry matter production (Wright et al. 1988), or both (Hocking et al. 1997). The distribution of N in canola plants varies depending on the growth stage of the plant. Prior to flowering, 76% of the N is in the leaves and 24% is in the stems (Schjoerring et al. 1995). As pod formation progresses, N moves from the leaves to the pod walls and eventually into the seed where upon maturity, more than 70% of the total plant N (including N in dropped leaves) resides (Schjoerring et al. 1995).

The concentration of N in plant tissue increases when the rate of N uptake and/or relocation exceeds that of biomass production. By applying 150 kg N ha^{-1}, Chamorro et al. (2002) increased N concentrations at the early budding stage by 31 and 46% in canola leaves and stems respectively, compared with the unfertilized check. By late flowering, the same fertilizer rate had increased N content by 40, 23, and 18% for the leaves, stems, and inflorescence respectively. Despite including six N rates in this study, Chamorro et al. (2002) did not report orthogonal contrasts in the analysis so it is impossible to comment on the shape of the responses. Similarly, Hocking et al. (2002) increased N concentration in canola stems at anthesis by 15 – 28% with 75 kg N ha^{-1}.

Increases in N uptake are typically not so much a result of N becoming more concentrated in the plant tissue, but increased biomass production. In a study conducted over 33 site-years and covering two degrees of latitude and longitude in Saskatchewan, Miller et al. (2003) assigned 73% of the variability in shoot biomass of *Brassica* crops to N fertility. They assigned 15% to environment and only 5% to cultivar. Likewise in Australia, Hocking et al. (1997) doubled the quantity of canola biomass produced at anthesis with as little as 50 kg N ha^{-1} in four out of seven site-years. Ten weeks after seeding, Mason and Brennan (1998) observed total quantities of N in canola biomass of 43, 58, 78, and 130 kg N ha^{-1} for N applications of 0, 23, 46, and 138 kg ha^{-1} respectively and commented that N uptake followed similar patterns over the growing season to biomass accumulation. At the rosette stage, Svečnjak and Rengel (2006) observed varying concentrations of N in plant tissues from one cultivar to the next, but the same total N uptake measured for each of four Australian spring cultivars. Taking in the same total quantity of N, some cultivars accumulated more biomass than others did and therefore, were more efficient in terms of N utilization (Svečnjak and Rengel 2006).

Increasing N uptake resulting from increasing N fertility is evident not only in canola plant tissue, but also in the grain. Malhi and Gill (2004) found that at optimum seeding depths, increasing the rate of side-banded urea caused the protein content of canola seed to increase linearly from 18.4% with no fertilizer N to 22.7% at 120 kg N ha^{-1}. In the same study, grain yield increased quadratically with N rate from 1293 kg ha^{-1} with no fertilizer N to 2228 kg ha^{-1} at 120 kg N ha^{-1}. That protein content increased linearly while grain yield increased quadratically indicates that canola protein content continues to increase at N rates beyond the point where there is an effect on grain yield.

However, as previously mentioned, increasing grain protein often occurs at the expense of oil content, thus reducing the overall end value of the canola seed. In the previous study (Malhi and Gill 2004), increasing the N application rate caused oil content to decrease linearly, whereby the canola grown without fertilizer had 47.3% oil content, compared with 41.8% for the canola seed grown at 120 kg N ha^{-1}. That end users and producers do not have the same incentives in terms of N management in canola may suggest a need to improve the current canola marketing system. If producers received premiums for high oil content, the economic N rates for producing canola would conceivably decrease along with the transportation and processing costs of canola seed.

2.3 NITROGEN FERTILIZER REQUIREMENTS

The optimum fertilizer N rate in crop production supplies only as much N as the crop can utilize, maximizes economic returns, and minimizes the potential for negative environmental consequences. Consequently, incentives against applying excessive quantities of fertilizer N rates come from both economic and environmental viewpoints. The amount of fertilizer N required by crops depends on yield potential, the quantity of N that the soil can provide, and the magnitude of N losses and immobilization. Failure of N fertilizer recommendations to account for any one of these factors results in either inadequate or excessive recommended fertilizer rates. Too little N leads to decreased grain yield and water-use efficiency (Taylor et al. 1991), while too much leads to decreased fertilizer N-use efficiency and increased potential for environmental contamination. Either of these outcomes means lost profits for producers because of uncaptured revenues in the former case and unnecessary expenses in the latter. The general model describing N fertilizer requirements of crops is presented in Equation 2.1:

$$N_f = N_c - (N_{sources} - N_{losses}) \tag{2.1}$$

where N_f is N fertilizer, N_c is the total quantity of N required by the crop, $N_{sources}$ is the sum of N sources available to the crop without fertilization, and N_{losses} are losses of N (Rice et al. 1995). In reality, however, this apparently simple equation is quite complex because various environmental factors affect each of these three variables.

2.3.1 Yield Potential

The total N requirements of crops are directly proportional to their yield potential (YP), with every 1960 kg ha^{-1} of canola seed produced removing approximately 76 kg N and 49 kg N ha^{-1} in the grain and straw respectively (Manitoba Agriculture, Food, and Rural Initiatives 2001). As such, for every 1960 kg N ha^{-1} of canola that producers expect to produce, they must ensure that there is a total of at least 125 kg N ha^{-1} available. The grain yield of crops is the culmination of the relationships between several abiotic and biotic factors, some of which are influenced by management practices and others that are largely beyond the control of producers.

Although typically required in smaller quantities, plants require several other nutrients besides N (Manitoba Agriculture, Food, and Rural Initiatives 2001). The most important of these are phosphorus (P), potassium (K), and sulphur (S); however, plants require nearly a dozen other nutrients, including calcium (Ca), magnesium (Mg), iron (Fe), and boron (B) (Havlin et al. 2005). While producers only rarely apply micronutrients to canola as fertilizer, any nutrient can potentially reduce grain yields in soils where it is limited.

At Irricana, Alberta, Karamanos et al. (2005) had to apply 20 kg P_2O_5 ha^{-1} to achieve maximum yield for two of three hybrid canola varieties. The remaining hybrid and a conventional variety required 40 kg P_2O_5 ha^{-1} before reaching maximum grain yield. McKenzie et al. (2003) observed significant canola yield responses to P at 45% of 108 separate canola fields in the brown, black, and grey soil zones of Alberta.

Potassium plays an important role in the physiological activity of plants and is required in large quantities for optimal crop production. Canola requires larger quantities of K than any other nutrient besides N, containing 93 kg K_2O ha^{-1} in the above ground portion of a 1960 kg ha^{-1} crop (Manitoba Agriculture, Food, and Rural Initiatives 2001). However, K is rarely limiting to canola yield in western Canada because our soils contain adequate supplies of this nutrient (Grant and Bailey 1993); thus very little K fertilizer is applied relative to other nutrients (Korol 2002). Furthermore, relatively little K is permanently removed from the soil by canola crops. While a healthy, high yielding canola crop contains 150 – 300 kg K_2O ha^{-1}, only 8 – 60 kg ha^{-1} is removed in the seed at harvest (Grant and Bailey 1993).

Although yield responses to S tend to be inconsistent, they can be sizeable in soils where S is limiting (Grant et al. 2004). In northeastern Saskatchewan, the addition of 5 kg S ha^{-1} increased seed yield by 143 – 608 kg ha^{-1}, depending on the variety (Malhi and Gill 2006). Further applications of 5 kg S ha^{-1} increased grain yield by an additional 174 – 243 kg ha^{-1}, at which point the canola typically reached maximum yield.

When water and nutrients are available in sufficient quantities, canola adapts well to low plant densities through increased growth per plant (Rood and Major 1984). As long as the plants are distributed evenly, canola yields are largely unaffected by plant populations ranging from 20 – 80 plants m^{-2} (Angadi et al. 2003). However, the ability of canola to maintain grain yields under decreasing plant populations tends to decrease considerably in drought years. In Saskatchewan, reducing plant densities from 40 to 20 plants m^{-2} reduced grain yields by 20% in normal years and by up to 36% in dry years (Angadi et al. 2003). The Canola Council of Canada recommends targeting approximately 75 – 150 plants m^{-2} (Canola Council of Canada 2005b).

For similar reasons, canola yield is largely unaffected by row spacing, yielding similarly at row widths between 15 – 38 cm (Xie et al. 1998; Johnson and Hanson 2003). Wider row spacing may benefit canola by reducing root maggot infestations (Dosdall et al. 2004) and flea beetle damage (Dosdall et al. 1999). However, as the distance between rows increases, banded N fertilizer becomes more concentrated, increasing the importance of adequate separation between seed and N fertilizer (Xie et al. 1998).

Adverse environmental conditions such as excessive heat and drought stress during flowering also negatively affect canola yields (Angadi et al. 2000; Morrison and Stewart 2002). On average, temperatures in western Canada are well suited for canola production (Table 2.2), but prolonged periods of extreme heat and dry soil conditions frequently occur late in the growing season. Angadi et al. (2000) found that subjecting canola plants at the early flowering stage to seven continuous days with maximum daytime temperatures of 35˚C reduced seed yield by 47% relative to daytime high temperatures of 20˚C. Subjecting canola to the same temperatures at the early pod-filling stage reduced grain yields by 12% relative to canola growing at moderate temperatures (Angadi et al. 2000). Morrison and Stewart (2002) reported that the threshold temperature at flowering beyond which canola grain yields begin to decline is 29˚C, which is consistent with Angadi et al. (2000) who found that daytime highs of 28˚ C did not reduce canola yields.

Table 2.2. Mean monthly high and low temperatures (˚C) for various locations in western Canada and Ottawa, ON.

Location[z]	May		June		July		August	
	Min[y]	Max[x]	Min	Max	Min	Max	Min	Max
	˚C							
Lethbridge, AB	4.6	18.2	8.8	22.4	10.7	25.6	10	25.2
Olds, AB	2.9	15.8	7.1	19.4	9.1	21.7	8.2	21.4
Beaver Lodge, AB	3.3	16.2	7.4	19.5	9.0	21.5	8.0	20.9
Swift Current, SK	4.5	17.6	9.2	22.0	11.3	24.8	10.8	25
Indian Head, SK	4.5	18.2	9.7	22.6	11.7	25.0	10.5	24.5
Scott, SK	3.9	17.8	8.7	21.7	10.4	23.6	9.2	23.3
Brandon, MB	4.4	19.2	9.8	23.5	11.8	25.9	10.5	25.4
Winnipeg, MB	4.8	19.2	10.7	23.3	13.3	25.8	11.9	25
Ottawa, ON	8.0	19.1	13.0	23.8	15.5	26.4	14.3	25

Data are from Environment Canada's online Climate Normals and Averages: www.climate.weatheroffice.ec.gc.ca/climate_normals [verified October 23, 2006].

[z] Refer to Table 2.3 for latitude and longitude of locations

[y] Average minimum temperature for the given month, 1971-2000

[x] Average maximum temperature for the given month, 1971-2000

While producers have very limited control over environmental factors such as temperature and moisture availability, in certain years the time of seeding can be important. In years where early seeded canola yields higher than late seeded canola, the difference is often attributable to the early seeded canola flowering during periods of higher moisture availability and cooler temperatures (Angadi et al. 2004). However, whether or not early seeding is advantageous depends on the weather patterns over the growing season and are variable from one year to the next. For instance in 2002 at Swift Current, where a warm, moist summer followed dry conditions early on, postponing seeding until the end of May resulted in grain yields that were 18% higher than for canola seeded in late April (Angadi et al. 2004).

Water availability is potentially the most important factor affecting canola yields in the northern Great Plains (Brandt and McGregor 1997; Johnston et al., 2002b). Mean annual precipitation levels in western Canada range from less than 350 mm at Swift

Current, SK to over 500 mm at Winnipeg, MB (Table 2.3). In the majority of the northern Great Plains; however, potential evapotranspiration exceeds total precipitation and moisture commonly becomes limiting late in the growing season (Johnston et al. 2002b). Canola is a deep-rooted crop capable of extracting water from depths of 114 – 165 cm and is often dependent on sub-soil moisture during flowering and pod filling (Johnston et al. 2002b). Brandt and McGregor (1997) developed a model whereby every degree Celsius increase in mean daily temperature decreased fallow canola yield by 187.7 kg ha^{-1} and each millimetre increase in growing season precipitation increased yield by 5.9 kg ha^{-1} (R^2 = 0.83).

Table 2.3. Geographic locations and mean temperature and precipitation for various locations in western Canada and Ottawa, ON.

Location	Lat. (N)	Long. (W)	Elevation	Temp.^{z}	Precip.^{y}
	degrees		m	˚C	mm
Lethbridge, AB	49.6	112.8	921	5.8	365
Olds, AB	51.8	114.1	1040	3.1	494
Beaverlodge, AB	55.2	119.4	745	2.3	461
Swift Current, SK	50.3	107.7	825	3.9	348
Indian Head, SK	50.6	103.7	579	2.6	447
Scott, SK	52.4	108.8	660	1.6	359
Brandon, MB	49.9	100.0	363	2.4	474
Winnipeg, MB	49.9	97.3	239	2.6	514
Ottawa, ON	45.4	75.7	79	6.3	914.2

Data are from Environment Canada's online Climate Normals and Averages www.climate.weatheroffice.ec.gc.ca/climate_normals [verified October 23 2006].

^{z}Mean annual temperature (1971-2000)

^{y}Mean annual precipitation (1971-2000)

Certain management practices can also influence both soil moisture levels and WUE of crops. Cutforth et al. (2006) reported that planting canola into fields that over-wintered with tall stubble increased grain yields by 16% and WUE by 11% relative to planting into cultivated stubble. Lafond et al. (2006) found that WUE was higher under zero-tillage management for flax, but zero tillage had no effect on WUE of field peas, winter wheat, or spring wheat.

Due to the variability of the various factors affecting canola YP and our inability to predict most of them at the time when N fertilizer is applied, yield goals chosen for the purpose of generating fertilizer recommendations, which will be discussed in greater detail in section 2.4, are often little better than educated guesses. One could argue that YP is one of the most important determinants of crop N fertilizer requirements and the most difficult to estimate at the start of the growing season.

2.3.2 Soil Nitrogen

Similar to YP, the extent to which a crop responds to fertilizer N is also directly proportional to the capacity of the soil to supply N. Soil N includes both mineral N available at the start of the season as well as any N mineralized from soil organic matter (SOM) during the growing season. The predominant forms of N in the soil that are readily available to plants are NO_3^- and NH_4^+. Nitrate occurs mainly in the soil solution while NH_4^+ exists both in solution and adsorbed to negatively charged surfaces of soil particles and SOM (Havlin et al. 2005). The quantity of residual N available to plants at the time of seeding is a function of the quantity of N carried over from the previous crop, over-winter N losses, and the rate and extent of mineralization in the fall and early spring. Discounting mineral soil N present in late fall or early spring from total N requirements is a widely accepted practice when calculating N fertilizer rates (Manitoba Agriculture, Food, and Rural Initiatives 2001). To produce 2.5 Mt ha^{-1} of canola, Manitoba Agriculture, Food, and Rural Initiatives recommends applying anywhere from 95 – 185 kg N ha^{-1}, depending how much fall soil NO_3-N is available (Table 2.4).

Mineralization is the biological conversion of organic N into NH_4^+. The chemical process of mineralization proceeds in two separate reactions, aminization and ammonification. Aminization is where microorganisms break complex proteins into amino acids, amides, and amines, while ammonification is the subsequent conversion of these products to NH_3, which, under normal conditions, quickly reacts with soil water and converts to NH_4^+ (Havlin et al., 2005). It is important also to consider biological immobilization when discussing the effects of mineralization of organic N, as the two processes occur simultaneously in the soil. Immobilization is the conversion of inorganic N to organic N and is essentially the microbe's means of maintaining a balanced diet. Generally when referring to mineralization or immobilization, what we usually mean is mineralization-immobilization turnover (MIT), or the net balance of the two processes.

Table 2.4. Nitrogen recommendations for canola in Manitoba (adapted from Manitoba Agriculture, Food, and Rural Initiatives 2001).

	Yield Goal (tonnes ha^{-1})			
	2.52	**2.24**	**1.96**	**1.68**
Fall Soil NO_3-N kg ha^{-1} (0-60 cm)	Recommended Nitrogen Rate^z kg N ha^{-1}			
22.4	179	151	118	84
33.6	162	129	95	62
44.8	140	106	78	45
56.0	123	90	62	28
67.2	112	78	45	17
78.4	101	67	39	6
89.6	95	62	34	0
101	95	62	28	0
112	95	62	28	0

^{z}Recommendations are based on spring broadcast application

The C/N ratio of decomposing crop residues is a well-recognized determinant of the dynamics of MIT. Under non-N-limiting conditions, Trinsoutrot et al. (2000) found that only residues with a C/N ratio lower than 24 had released mineral N after 168 days from application. Similarly, Soon and Arshad (2002) reported that, on an annual basis, pea residues decompose more rapidly and release more N than canola or wheat residues. Furthermore, the rate at which residues decompose tends to accelerate with the addition of N fertilizer (Soon and Arshad 2002). Because they do not require N fertilizer and have relatively low C/N rates, pulse crops improve the overall NUE of rotations and can have residual N benefits for subsequent crops. Beckie and Brandt (1997) recommended that for each tonne of field peas produced the previous year, producers should credit 13 and 4 kg N ha^{-1} at Melfort (Orthic Black Chernozem) and Scott (Orthic Dark Brown Chernozem) respectively. However, the amount of N that producers should credit will vary from one year to the next. In 1994 at Melfort, the economic N rate for flax grown on pea stubble was only 41 kg ha^{-1} compared with 102 kg ha^{-1} for flax on wheat stubble, while the difference in the following year was only 13 kg ha^{-1} (Beckie and Brandt 1997).

In addition to the total N content and C/N ratios of residues, the chemical structure of the organic N and C also affects the direction and rate of MIT. Some of the soil properties with which N mineralization is correlated are organic C (R^2 =0.78), total N (R^2=0.70), light fraction C (R^2=0.76), and light fraction N (R^2=0.78; Campbell et al. 1999). While total N and C/N ratios have a greater effect on MIT dynamics over the long-term, the ease with which organic C decomposes is important in the short term. For example, Trinsoutrot et al. (2000) found that including soluble polyphenol concentrations of crop residues in a multiple regression model significantly improved the relationship between various soil quality parameters and MIT for the first four weeks following incorporation. When only organic N content was included, the coefficients of determination for the model were 0.70 and 0.86 for seven and 28 days after application respectively. Including polyphenol concentrations increased the coefficients of determination to 0.84 and 0.94 respectively. After 28 days, including polyphenol concentrations no longer improved the MIT model (Trinsoutrot et al. 2000). Mulvaney et al. (2001) identified amino sugar N as being correlated with both grain yields of unfertilized check plots ($R = 0.79$) and to the responsiveness of the crop to fertilizer N ($R = -0.82$). Non-responsive soils had amino sugar N concentrations 33 – 1000% greater than those where crops responded to fertilizer N, while there were no consistent differences in total hydrolysable N, hydrolysable NH_4-N, or amino acid N (Mulvaney et al. 2001). All of this evidence suggests that, as with organic C, the 'quality' of organic N is important in determining if, and especially when, MIT is likely to result in the release of mineral N.

Soil moisture and temperature conditions cause large amounts of variability in MIT from one year to the next. Akinremi et al. (1999) found that on average, 4, 78, and 81% of the daily variation in CO_2 flux in fallow plots was explained by soil temperature, soil moisture, and the interaction between the two respectively. In barley plots, the trends were similar but the correlations were not as strong (Akinremi et al. 1999). This is consistent with Campbell et al. (1999), who also found that the interaction between soil moisture and temperature along with precipitation were the most important factors affecting MIT. They attributed the negative effect of the interaction between soil moisture and temperature interaction to increased in-situ N release under warm, moist conditions, which led to reduced mineralization in the subsequent laboratory incubations (Campbell et al. 1999). Under field conditions, the inverse relationship between soil temperature and moisture often results in a poor or even negative correlation between soil temperature and respiration, with soil temperature only having a positive effect when moisture availability is adequate (Akinremi et al. 1999).

Another important source of variation in residue decomposition and N mineralization rates is the frequency and intensity of drying and rewetting cycles, whereby a flush of rapid mineralization typically follows the rewetting of dry soils (Mikha et al. 2005; Miller et al. 2005). On soils that were dried and rewetted on intervals of either two or four weeks, Miller et al. (2005) measured cumulative CO_2 releases that were 2.2 – 3.7 times greater than those from soils maintained at the equivalent mean moisture content. Peak respiration rates from soils that were rewetted on two-week intervals were approximately half those of soils rewetted every four weeks, thus the cumulative CO_2 release from the two treatments was similar (Miller et al. 2005). However, the effects of repeated drying and rewetting events on cumulative net N mineralization are not always necessarily positive. After 96 days of rewetting on 24-day intervals, Mikha et al. (2005) found the total N release was reduced by 15 $\mu g\ N\ g^{-1}$ soil relative to soil maintained at constant moisture content.

The rapid flush of mineralization that often follows wetting of dry soils is due partly to microbial death during both the desiccation and rewetting processes (Bottner 1985; van Gestel et al. 1993), and partly to increased exposure of organic residues caused by the physical disruption of the soil (Cosentino et al. 2006). During periods of decreasing water availability, equilibration of microbial cells occurs either passively through osmosis, or actively through the accumulation of intercellular solutes (Bottner 1985). During extremely dry conditions, microbial cells relying on passive equilibration may die from dehydration (Bottner 1985). Meanwhile, prompt wetting of microbial cells that have adjusted to dry conditions results in either (1) passage of water through cell walls leading to increased turgor pressure and potentially cell lysis, (2) disposal of cell solutes by catabolism to CO_2, or (3) transport of intercellular solutes out of cells (Mikha et al. 2005). Each of these outcomes has the result of immediately releasing cell solutes that quickly become available to surviving microbes (Mikha et al. 2005).

Crop rotations and tillage systems are management factors that affect the soil environment such that there are implications for mineralization of SOM. In various field experiments in Saskatchewan ranging from 8 – 25 years in duration, continuous cropping increased C sequestration by 0.5 – 6.7 Mg C ha^{-1} compared with rotations that contained a fallow period and no-tillage fields sequestered 0.6 – 13.2 Mg ha^{-1} more C than conventional tillage fields (Liang et al. 2003). In the same plots, continuous cropping increased soil organic N by 7 – 17, 30, and 29 kg N ha^{-1} $year^{-1}$ in the Brown, Dark Brown, and Black Chernozem soils respectively (Liang et al. 2004). Relative to conventional tillage systems, no-till increased the amount of organic N in the soil by 16 – 28, 35 and 40 kg N ha^{-1} $year^{-1}$ in the Brown, Dark Brown, and Black Chernozem soils respectively (Liang et al. 2004). Similarly, there is evidence that net immobilization occurs more frequently in no-till soils than in conventionally tilled soils (Lupwayi et al. 2006), especially in the years immediately following conversion to no-till. Nonetheless, as no-tillage soils mature, they become less responsive to fertilizer N, indicating that the immobilization occurs less intensely in long-term no-till fields than in recently converted fields (Lafond 2003; Campbell et al. 2007).

2.3.3 Losses of Nitrogen

Crops typically recover less than 50% of the applied fertilizer N during the year of application and approximately 65% over a period of five growing seasons (Krupnik et al. 2004). Raun and Johnson (1999) estimated that worldwide fertilizer NUE in cereal production was only 33%, although in more temperate regions fertilizer recovery may be as high as 70% (Malhi et al. 2001). While this inefficiency is certainly not entirely due to N being lost from the soil-plant environment, taking measures to minimize losses of applied N will increase the overall efficiency of the fertilizer. The principle mechanisms by which unutilized N is lost from the soil-plant interface are leaching, denitrification, and volatilization. Immobilization is not generally considered a true loss because it does not remove N from the soil – plant environment; however, it can render applied N unavailable to crops for a certain period of time (Havlin et al. 2005).

Leaching occurs when water carries mineral N, usually NO_3^-, downward through the soil below the rooting zone. Nitrate is highly soluble in water and the potential for anion exchange sites to retain NO_3^- is limited, thus NO_3^- tends to be very mobile in the soil (Havlin et al. 2005). The potential for leaching is greatest when both NO_3^- concentrations and soil moisture content are high (Akinremi et al. 2005). Because of the relatively dry climate and low intensity agriculture that is characteristic of much of the prairies, the potential for NO_3^- leaching in these regions is relatively low in comparison to southern British Columbia and parts of central Canada (Reynolds et al. 1995). In general, sandy soils with low water holding capacity (WHC) and low cation exchange capacity (CEC) are most susceptible to leaching, although macropore flow can potentially result in high losses in clay soils (Clough et al. 1998).

Certain management practices increase the potential for leaching by allowing NO_3^-, water, or both to accumulate. Some examples of such practices are summerfallow (Campbell et al. 1984; Campbell et al. 1994), over-fertilization, and under-fertilization (Campbell et al. 1984). Tillage practices themselves do not generally affect the potential for leaching as long as continuous cropping is practiced (Jiao et al. 2004). Under the assumption that 10% of the added N and 10% of that mineralized from organic matter is lost via leaching, Janzen et al. (2003) estimated that 0.43 Tg N may be lost from Canadian agroecosystems each year. However, this estimate likely errs on the high side as we would expect little or no leaching for substantial areas of the prairies, most notably the native grasslands.

Denitrification occurs when O_2 is depleted from the soil and anaerobic organisms must seek alternative oxygen sources such as NO_2^- and NO_3^- (Cho 1982). Consequently, denitrification losses in western Canada are typically greatest during the spring snowmelt period (Pennock et al. 2005) and after heavy precipitation events (van Kessel et al. 1993). Depending how far the organisms proceed down the denitrification pathway ($NO_3^- \rightarrow NO_2^- \rightarrow NO\uparrow \rightarrow N_2O\uparrow \rightarrow N_2\uparrow$), gaseous losses of N typically occur as either N_2O or N_2. Well et al. (2006) observed total fertilizer N losses (N_2O plus N_2) of 10, 0.4, and approximately 0% of the applied N from soils maintained at 85, 75, and 55% water filled pore space respectively. Denitrification, as opposed to nitrification, was the main cause of N_2O emissions in soils maintained at 75% water filled pore space or wetter (Well et al. 2006). Denitrification losses are typically greatest in depressional areas of fields where moisture is likely to accumulate (van Kessel et al. 1993; Tiessen et al. 2005).

The last major process by which N is lost from the soil – plant system is volatilization, which occurs when NH_3 escapes from the surface of an ammoniacal solution into the free atmosphere. Immediately above the soil-air interface is a laminar layer of air through which NH_3 moves by molecular diffusion (Sommer et al. 2004), the rate of which is primarily controlled by temperature and the concentration gradient of the substance of interest. Above the laminar layer is a turbulent layer where the concentration gradient still determines the net direction of diffusion, but other factors such as surface roughness, wind speed, and atmospheric conditions also influence the exchange of gasses between the soil and the free atmosphere (Sommer and Ersboll 1996; Sommer et al. 2004).

The rate and extent to which volatile losses occur depends on many factors in addition to those previously mentioned. Some of these factors are the total quantity of ammoniacal N (Vlek and Stumpe 1978), the formulation of the N source, the initial pH of the soil and that of the fertilizer reaction zone (Sommer et al. 2004), soil moisture content (Al-Kanani et al. 1991), soil temperature (Fenn and Kissel 1974), and soil texture (Purakayastha and Katyal 1998). Surface evaporation accelerates volatilization both by drawing water upwards and by increasing the concentration of total ammoniacal N in solution (Al-Kanani et al. 1991). Similarly, precipitation following surface applications of N decreases emissions by moving the N deeper into the soil profile. As little as two mm of rain within two hours of the N being applied reduced NH_3 emissions from simulated urine by 15%, while 12 mm within two hours reduced emissions by 81% (Whitehead and Raistrick 1991). The greatest potential for volatile losses of N occurs when hot, dry conditions follow surface applications of fertilizers containing urea to wet soils (Stumpe and Monen 1986).

The simplest and most effective method of protecting N fertilizer from volatilization is to place it beneath the soil surface. Producers can achieve this by either incorporating volatile N sources into the soil immediately after application (Schilke-Gartley and Sims 1993), or by banding or nesting fertilizers beneath the soil surface using specialized application equipment (Janzen et al. 1990; Johnston et al. 2002a). Urease inhibitors, such as N-(*n*-butyl) thiophosphoric triamide (NBPT) slow the hydrolysis of urea and have the dual benefit of reducing both NH_3 emissions (Rawluk et al. 2001) and seedling toxicity (Grant and Bailey 1999). Using NBPT in Manitoba, Rawluk et al. (2001) reduced volatile losses from surface applied urea by 37 – 85%, depending on the texture of the soil and the timing of the fertilizer application.

In situations where subsurface banding is impractical, such as during the growing season or for established forages, surface-dribble banding (SDB) liquid urea-ammonium nitrate (UAN) is a viable option for producers. While applying N in this manner increases the risk of volatile losses compared with low-disturbance in-soil application methods such as coulter banding or point injection (Roberts et al. 1992), there are advantages to doing so. Any field sprayer used to apply pesticides, which the majority of producers already own, is easily equipped to apply liquid UAN in a SDB. Spoke wheel injectors and coulter applicators are relatively expensive, high maintenance, and have no other use besides liquid fertilizer applications. Research completed with spring wheat and canola has shown that the potential advantages of low-disturbance, in-soil placement of UAN relative to SDB applications are probably not sufficient to justify the added cost of specialized application equipment (Holzapfel et al. 2007). With approximately 50% of its N coming from urea and 50% from ammonium nitrate (AN), UAN is about 25% less susceptible than urea to volatilization if both products are applied similarly (Havlin et al. 2005).

Because losses of N are inevitable to a certain extent, producers must account for losses when deciding how much fertilizer to apply. While sound management practices and the adoption of improved application technology go a long way towards reducing N losses, the extent to which they occur still depends largely on environmental conditions and is difficult to predict. Clearly, the simple equation presented at the beginning of section 2.2 does not describe the true complexity of the various factors that affect fertilizer N requirements. A more accurate version of the previous model appears in Equation 2.2:

$$N_f = N_c - [(N_m + N_{in)} - (N_l + N_d + N_v) - N_{im}] \qquad [2.2]$$

where N_f is the quantity of fertilizer N required; N_c is the total N required to produce a crop of a given yield; N_m is N released from crop residues and mineralized from SOM, N_{in} is residual, plant available inorganic N; N_l, N_d, and N_v are N losses through leaching, denitrification, and volatilization respectively; and N_{im} is N made temporarily unavailable through immobilization (adapted from Rice et al. 1995). Visualizing the above equation expanded to include the many factors that affect each of its variables helps to demonstrate why it is so difficult to determine appropriate fertilizer N rates. Despite the impossibility of calculating N requirements with complete certainty, many tools are available to help bring us closer to doing so.

2.4 DETERMINING OPTIMUM NITROGEN FERTILIZER RATES

The majority of N recommendation models used in the Great Plains involve estimating a crop's N requirements based on a specific yield goal and crediting for residual soil N and potentially mineralizable N from SOM, previous manure applications, and/or previous legume crops. Factors such as previous crop, tillage practices, time of soil sampling, available soil moisture, and the ratio between the cost of N and the price of grain are also often considered when deciding on N fertilizer rates (Schlegel et al. 2005).

One of the most important limitations common to traditional models for estimating fertilizer requirements is the uncertainty of yield goals, which is an estimate of the yield that a producer expects, or hopes, to produce for a field. Johnston and Dowbenko (2006) suggest looking at the production of a given crop in a field for the past seven to ten years, removing any yields that are low because of drought or bad management, and averaging the yields from remaining years as one method of setting realistic yield goals. In addition, yield goals should be flexible to allow for adjustments of 10 – 20% either way for current economic considerations (Johnston and Dowbenko 2006) and/or spring soil moisture conditions (Andreiuk 2004). Depending on what yield goal producers choose, the recommended N fertilizer rate can vary extensively (Table 2.4). As such, yield goals are a poor indicator of optimum N rates when used on their own ($R^2 = 0.05$), presumably because of variability in N supply between fields and the unpredictability of growing season climatic conditions (Scharf 2001).

Estimating the soil's capacity to supply N is also not an easy task. While factors such as residual N levels and plant tissue N levels can be used to estimate N requirements and can be directly measured, the qualities that affect soil N availability tend to be highly variable over space and time (Section 2.3.2). Furthermore, proper sampling, storing, processing, analyzing, and interpretation are critical for using these tests effectively. Errors during any one these steps will discredit the outcome of these types of tests and can potentially result in an incorrect N fertilizer recommendation. The major tests that producers commonly use to estimate crop N requirements fall into two major categories, those that are based on soil measurements and those where the plants themselves are used as indicators of N status.

2.4.1 Soil-Testing

Soil tests are chemical extractions of soil nutrients from soil samples intended to estimate nutrient availability for the field from which the sample was collected. Both NO_3^- and the NH_4^+ in solution are extractable from soil samples using water as an extractant. Estimating exchangeable NH_4-N requires stronger extractants such as KCl. When KCl extractants are used, dissolved anions (Cl^-) replace NO_3^- on the positively charged exchange sites, while dissolved cations (K^+) replace NH_4^+ on the negatively charged sites. Increased concentration of extractants result in larger quantities of N released during the extraction. The information derived from soil tests is typically used to provide the user with information on the basic physical and chemical properties of soils including texture, cation-exchange capacity, pH, and salinity and to provide an index of nutrient availability in a field that can subsequently be used as a basis for recommending fertilizer rates (Havlin et al. 2005).

Collecting representative samples is the most critical step of soil testing. When sampling to estimate availability of N, it is important to sample to a depth of at least 60 cm because N is highly mobile in the soil profile and extracted by crops from greater depths than P or K. The appropriate sampling procedure for a field depends primarily on the objectives of the test. Sampling to determine the average nutrient availability for a field requires a different approach than sampling to describe spatial variability in a field. While the former is the more common of the two objectives, more intensive sampling is required if the objective of the test is to direct site-specific fertilizer applications.

Manitoba Agriculture, Food, and Rural Initiatives (Manitoba Agriculture, Food, and Rural Initiatives 2001) recommend using one of two methods for determining a field average for nutrient requirements. Traditional composite sampling involves collecting 15

– 20 cores randomly from a field, thoroughly mixing them, and sending a single sub-sample to the laboratory for analysis. With this approach, samples are taken only from representative areas of the field, taking care to avoid obvious unusual areas such as saline patches, depressions, old manure piles, fence-lines, headlands, etc. In hilly fields, samples are collected from mid-slope positions to obtain average results. A second approach, benchmark sampling, involves selecting one or two small areas that are representative of the majority of the field and collecting 15 – 20 samples randomly within the selected benchmark areas. This method accelerates the sampling process because, at most, only a few areas of the field require sampling, as opposed to the entire field as in random sampling. The downside of either of these two sampling methods is that neither describes spatial variability in residual N levels, which can be high (Franzen et al. 1998; Raun et al. 1998). Collecting soil samples every 0.09 m^2 from established bermudagrass sites and accounting for both soil residual NO_3^- and NH_4^+, Raun et al. (1998) found that the recommended fertilizer rates within each 45 m^2 ranged from 32 – 57 kg N ha^{-1}. While variability at such high resolution is not practical to address using soil samples, this example illustrates how much variability can exist in apparently uniform fields.

Variable-rate fertilizer applications based on soil-test N require that samples be carefully labelled and sites georeferenced using global positioning systems (GPS). The most common sampling strategies for characterizing spatial variability are grid-soil sampling and landscape-directed sampling. In the case of grid sampling, samples are collected from grids of a specified size located systematically across the entire field, analyzed separately, and mapped (Manitoba Agriculture, Food, and Rural Initiatives 2001; Rains et al. 2001). In contrast, landscape directed sampling involves classifying fields into distinct zones according to traits such as cropping history, landscape position, or soil texture and sampling them accordingly (Manitoba Agriculture, Food, and Rural Initiatives 2001; Rains et al. 2001). While landscape-directed sampling usually requires less intensive sampling, Chang et al. (2003) found that grid sampling reduced within zone variability more consistently than landscape directed sampling. In contrast, Franzen et al. (1998) found that landscape directed sampling did a much better job of describing N fertility patterns than grid sampling on a 0.45 ha grid. Furthermore, collecting samples from a wide area within each landscape zone is generally preferred over point sampling for each zone (Franzen et al. 1998). While there is no real consensus as to whether grid sampling or landscape directed sampling is preferable, grid sampling may be more appropriate when there is no logical reason to believe that variability exists, while landscape-directed sampling would likely be the preferred method in more hummocky terrain or in fields with known sources of variability.

Despite the widespread acceptance of soil tests as a tool for determining N fertilizer requirements, they have important limitations. Currently, none of the tests commonly used in soil labs measure organic N or the mineralization potential of the soil. Alternative soil N availability indices, such as hydrolyzed hot KCl N (Jalil et al. 1996), Electro-Ultra-Filtration (Mengel et al. 1999; Mengel et al. 2006) N, and the Illinois Soil Test N (Khan et al. 2001), measure fractions of organic N that are correlated with, but not equal to, cumulative mineralized sources of N. The fraction of organic N measured by the Electro-Ultra-Filtration and Illinois Soil Test N methods mostly consists of amino and amino sugar N, both of which are readily mineralized N sources (Mengel et al. 1999). Soils that are responsive to fertilizer N often have low quantities of light organic fractions of N relative to soils where crops do not respond to fertilizer N (Khan et al. 2001; Mulvaney et al. 2001). Calculating fertilizer rates for cereals based on Electro-Ultra-Filtration extractable N, Mengel et al. (2006) substantially reduced N rates and, in 18 out of 23 cases, produced equal or greater grain yields than those where fertilizer rates were determined using mineral N measurements.

While light fractions of organic N have been frequently shown to be correlated with mineralization or crop responsiveness to N fertilizer, environmental factors such as weather make predicting cumulative mineralization difficult. Walley et al. (2002) concluded that soil N availability indices were generally no better at explaining variability in crop N accumulation than basic soil properties or relative elevation. Walley et al. (2002) stressed that soil N availability indices are only likely to be useful for predicting fertilizer N requirements as they vary over space if combined with some other information about field-scale variability (Walley et al. 2002). Consequently, it is highly unlikely that soil N availability indices will ever be able to predict N release from the soil during the growing season with complete accuracy.

2.4.2 Crop-Based Indicators

Crop-based indicators of N status can be very useful for fine-tuning N recommendations because they simultaneously account for both plant N demands and soil N availability (Ma et al. 2005). A plant growing in its natural environment is the "ultimate integrator of environmental variables controlling the N transformations with the soil N cycle and, ultimately, the N available to it (Rice et al. 1995)." As such, comparing crop-based indicators from plants growing under possibly N limiting conditions with those of unfertilized plants can help determine whether there has been a response to applied N (Raun et al. 2002). Alternatively, comparing them with those of plants grown under non-N limiting conditions helps determine the likelihood of a response to further additions of N (Raun et al. 2002). Havlin et al. (2005) identify the main purposes of plant analyses as to identify nutrient deficiencies before they appear as visual symptoms, to help determine the nutrient supplying capacity of the soil, to help determine the effects of fertilizer additions on the nutrient supply in the plant, and to study the relationship between agronomic performance and nutrient status of the plant.

Tissue testing is the most traditional of plant analysis and typically involves measuring the nutrient concentrations of crops at specific growth stages and comparing them with established values to determine if each nutrient is deficient, adequate, or excessive for the crop under analysis (Manitoba Agriculture, Food, and Rural Initiatives 2001). In Manitoba, 2.5 – 4.0% N content is considered sufficient for the entire tops of canola during flowering (Manitoba Agriculture, Food, and Rural Initiatives 2001). As with soil testing, following proper sampling and handling procedures is critical for the results of plant tissue analyses to be reliable indicators of N requirements. However, sampling an adequate number of representative plants to use plant tissue analysis to characterize the N status of a crop as it varies across the landscape is generally not considered practical for the same reasons that soil test analyses are not practical for such purposes.

While plant N content and optimum N fertilizer rates are correlated (Scharf 2001) and established critical values exist for most crops (Manitoba Agriculture, Food, and Rural Initiatives 2001), indirect methods of doing essentially the same thing exist that do not have the lag time of laboratory analyses. Such methods are based on the unique reflective characteristics of plant leaves and/or crop canopies. As the concentration of chlorophyll in leaves increases, the amount of visible electromagnetic radiation (EMR), which corresponds to wavelengths approximately 400 – 700 nm, reflected from their surfaces decreases (Daughtry et al. 2000). In contrast, as the bandwidth approaches the near infrared (NIR) portion of the spectrum (700-1000 nm), most irradiated EMR is reflected by leaf tissue (Daughtry et al. 2000; Major et al. 2001). Due to the effects of N fertility on leaf area index, biomass and soil cover, canopy reflectance of EMR in the visible and middle infrared regions decreases with increasing N fertilizer rates, while reflectance of NIR irradiance increases (Walburg et al. 1982). In short, the spectral response to plant stress is associated with chlorophyll in the visible, leaf structure in the NIR, and plant water in the middle infrared regions of the spectrum (Daughtry et al. 2000; Major et al. 2001).

While cultivar, growth stage, and availability of other nutrients all affect leaf chlorophyll status, N availability is usually the greatest source of variation within individual fields on a given year (Spaner et al. 2005). Chlorophyll meters are handheld instruments designed to measure the reflectance of individual leaves. The SPAD 502^{TM} (Minolta) and N-Tester^{TM} (Hydro-Agri) are two chlorophyll meters that use light-emitting diodes of approximately 650 nm and 940 nm to produce reflected EMR values that, although not the same, are highly correlated with one another ($R^2 = 0.98$; Arregui et al. 2006). Readings from both meters are well correlated with both the N status and relative grain yields of the crops being measured, and are thus useful tools for identifying N deficiencies in crops (Spaner et al. 2005; Arregui et al. 2006). Unfortunately, the critical values required for reliable N recommendations vary between cultivars, growth stages, and from one year to the next (Spaner et al. 2005). As such, it is generally more useful to compare readings of a crop with both unfertilized and non-N limiting plots to determine if there has been a response to applied N, and whether a response to further additions of N could be expected (Blackmer and Schepers 1995). Ultimately, however, the variability of the critical values produced by chlorophyll meters and the intensiveness of the sampling procedure limit utility in precision agriculture applications.

Better suited for the purposes of precision agriculture, multi-spectral satellite images provide information on the spectral characteristics of crops over large areas, allowing spatial patterns in fields to be characterized (Basnyat et al. 2005). In addition to covering large areas of the earth's surface, historical satellite images are available going back many years. Consequently, it is easy to choose images from years with varying precipitation to characterize spatial variability in crop parameters for a range of moisture conditions and identify zones that are temporally stable (Basnyat et al. 2005).

However, as with all technological solutions, satellite-mounted sensors are not without problems and limitations. These sensors are all passive, meaning that they do not emit their own light source, but rely on the sun as a source of EMR. Relying on the sun as a light source becomes problematic under variable cloud conditions, which can make it virtually impossible to acquire usable data from satellite-mounted sensors (Marshall et al. 1994). Furthermore, dense cloud cover can completely conceal substantial areas of the images, which renders them useless if the area of interest happens to be under a cloud. The satellite's orbiting pattern and the geographic location of the field of interest dictate how frequently and on what days images are available. Thus, if an image is unusable, the purchaser has no other option but to wait for the field to come back into the sensor's field of view. While attaching passive optical sensors to aircraft (Shanahan et al. 2001) or hydraulic lifts (Broge and Mortensen 2002) eliminates the restrictions associated with satellite orbiting patterns, doing so is expensive and variable cloud conditions can still cause problems.

The spectral response of crop canopies is somewhat more complex than that of individual leaves; therefore, the spectral signatures of crop canopies are usually described using vegetation indices (VI) calculated from the reflectance values of specific bandwidths. The purposes of VI are to enhance the spectral reflectance of plant fractions while minimizing the spectral effects of background soil, light intensity, sun angle, senescent vegetation, and atmospheric conditions (Major et al. 2001; Broge and Mortensen 2002). Vegetation indices are useful for assessing characteristics such as plant leaf area, total biomass, and the overall health and vigor of the surface vegetation (Major et al. 2001; Broge and Mortensen 2002). While scientists have proposed dozens of VI over the years, most of them are calculated using only visible and NIR bands and involve relatively simple mathematics (Broge and Mortensen 2002). Relatively complex indices involving waveform analysis of hyperspectral reflectance data are available; however, Broge and Mortensen (2002) found that they were typically no better at estimating the greenness (green crop area index) of winter wheat canopies than traditional indices, although they did generally improve estimates of canopy chlorophyll density. However, hyperspectral data is considerably more costly, difficult to acquire, and complicated to process than broadband remotely sensed data.

One of the earliest VI proposed was the ratio vegetation index (RVI), also known as the simple ratio index (Jordan 1969). Jordan (1969) recognized that while the intensities of red and NIR irradiation that penetrated through the forest canopy vary considerably throughout the day and over the course of the year, the ratio of the two remained almost constant throughout. While this VI would be modified in innumerable ways in coming years, the normalizing effect of expressing visible and NIR irradiation as a ratio is fundamental to most of the more widely accepted VI today. Ratio VI is calculated using Equation 2.3:

$$\mathrm{RVI} = \rho_{\mathrm{nir}} / \rho_{\mathrm{vis}} \qquad [2.3]$$

where ρ_{nir} and ρ_{vis} are the quantities of NIR and visible light reflected respectively.

When crops become limited in N, canopy reflectance of visible light increases while reflectance of NIR irradiance decreases, thus RVI is more sensitive to subtle changes in N status than any single wavelength on its own (Walburg et al. 1982). Relative to other indices, RVI is unique in that a linear equation best explains its relationship with most crop parameters, while exponential equations are generally best for other VI (Broge and Mortensen 2002). Using a fourth order polynomial equation, RVI was closely related to the green leaf area index (LAI) of barley canopies (R^2=0.993) up to RVI values of about 3, at which point this index became insensitive to further increases in LAI (Petersen et al. 2002). Overall, barley responses to N fertilizer as indicated by RVI were similar and consistently significant over two years from the 1-3 leaf stage of barley all the way through grain ripening (Petersen et al. 2002). Elwadie et al. (2005) identified RVI as being highly correlated with grain yield in the late vegetative and early reproductive stages of corn. The relationship between RVI and grain yield progressively improved during the growing season, peaked at the R5 dent stage, and collapsed with the onset of maturity (Elwadie et al. 2005)

A few years following the introduction of RVI, Rouse et al. (1974) proposed the VI currently known as NDVI. Normalized difference vegetation index is calculated by dividing the difference in visible and NIR radiation by their sum (Equation 2.4) and is among the most commonly used VI today.

$$\mathrm{NDVI} = (\rho_{\mathrm{nir}} - \rho_{\mathrm{vis}}) / (\rho_{\mathrm{nir}} + \rho_{\mathrm{vis}}) \qquad [2.4]$$

RVI and NDVI are functionally equivalent to one another through equation 2.5.

$$\mathrm{NDVI} = (\mathrm{RVI} - 1) / (\mathrm{RVI} + 1) \qquad [2.5]$$

However, the two indices differ in their range of values. In practical terms, the possible range of -1.0 to 1.0 for NDVI is easier to work with than the infinite range of RVI.

Normalized difference vegetation index is well suited for estimating a number of different crop production characteristics that vary with N fertility. Moges et al. (2004) found that NDVI (calculated using red visible as opposed to green visible reflected EMR) was exponentially related to winter wheat forage biomass from Feekes growth stage four (R^2=0.78) through to Feekes growth stage ten (R^2=0.60), with an overall tendency for the correlation to decrease with increasing growth stage. The correlation between forage N uptake and NDVI was also strong, remaining significant from Feekes growth stage four through Feekes growth stage ten and peaking at Feekes growth stage six (R^2=0.91). Freeman et al. (2007) found that during the V8 – V10 growth stages of corn, NDVI was a relatively poor predictor of the biomass of individual plants (R^2=0.31), but well suited for predicting corn forage biomass per unit area (R^2=0.52) and very well suited for estimating N uptake (R^2=0.61) of corn.

Because of the relationships between early season crop growth and grain yield, there is often a strong correlation between in-season NDVI measurements and grain yields. Corn yields corn yields have shown to be highly correlated with both absolute and normalized NDVI measurements collected throughout the growing season (Shanahan et al. 2001; Teal et al. 2006). The concept of normalizing NDVI is discussed further in the next section. However, the relationship between grain yield and NDVI differs somewhat depending on the source of visible light used. The relationship between green NDVI and grain yield remains strong later into the growing season than red NDVI, while red NDVI is generally better suited than green NDVI for predicting grain yields early on (Moges et al. 2004).

Basnyat et al. (2005) successfully used NDVI to delineate management zones by clustering NDVI information from Landsat TM images into distinct groupings. Over four years, the two zones identified yielded differently and had different grain protein contents. In addition, the two zones responded differently to fertilizer in that there was no response to fertilizer N or P in the zone with higher NDVI values compared with a significant response in the zone with lower NDVI (Basnyat et al. 2005). When acquiring imagery of canola crops for such purposes, however, it is important to do so before the crop reaches full bloom, as the highly reflective flowers and dropping of leaves are problematic when relating NDVI to grain yield (Basnyat et al. 2004). Furthermore, there is evidence that the absolute NDVI values of canola canopies measured at any given growth stage may vary from one cultivar to the next (Behrens et al. 2004). Consequently, the relative NDVI values within a field tend to be more meaningful than the absolute values when using NDVI to delineate different fertilizer management zones.

An important drawback of both RVI and NDVI is that both are sensitive to the optical properties of the background soil (Baret and Guyot 1991). The soil line is the linear relationship between NIR and red reflectance of bare soil. If you were to plot pixels from a satellite image with ρ_{red} on the X axis and ρ_{NIR} on the Y, the lower, right boundary of the points is almost linear and taken to be made up of pixels containing only bare soil and, hence is referred to as the soil line. The area of the plot opposite from the soil line, where ρ_{NIR} is at a maximum and ρ_{red} is at a minimum, is composed of pixels representing areas covered with dense vegetation (Fox et al. 2004). All points representing pixels characterized by a mixture of bare soil and vegetation fall somewhere between these two extremes. Mathematically, the definition of the soil line is:

$$\rho_{\mathrm{nir}} = a(\rho_{\mathrm{vis}}) + b \qquad [3.6]$$

where a is the slope and b is the intercept. While both RVI and NDVI assume that the soil line has a slope of one and converges at the origin (Qi et al. 1994), the parameters a and b can vary significantly from one soil to the next (Fox et al. 2004). The origin is the position in NIR-red space where the reflectance of both bandwidths is zero.

Several soil characteristics including colour, residues, and moisture content affect the reflectance properties of bare soil (Daughtry et al. 2000; Nagler et al. 2000), thus creating noise in VI that have no adjustment for soil reflectance. Dark or wet soils typically have higher RVI and NDVI values than light coloured or dry soils with the same amount of vegetative cover (Huete 1988; Nagler et al. 2000). However, the effects of soil moisture on surface reflectance decrease with increasing vegetative cover (Daughtry et al. 2000). Several VI, including soil-adjusted vegetation index (SAVI; Huete 1988) and the transformed soil adjusted VI (TSAVI; Baret and Guyot 1991) have been proposed to decrease the sensitivity of VI to variability in background soils.

Huete (1988) introduced SAVI in hopes that it would reduce the effects of background soil compared to NDVI or RVI. The mathematical definition of SAVI is:

$$\mathrm{SAVI} = \left(\frac{\boldsymbol{\rho}_{\mathrm{nir}} - \boldsymbol{\rho}_{\mathrm{vis}}}{\boldsymbol{\rho}_{\mathrm{nir}} + \boldsymbol{\rho}_{\mathrm{vis}} + \boldsymbol{L}} \right) (1 + \boldsymbol{L}) \qquad [2.7]$$

where *L* is a constant that should be set to approximately 1, 0.5, or 0.25 for low, medium, and high density canopies, respectively (Huete 1988). While *L* is commonly set to 0.5, doing so reduces the vegetation dynamic response of SAVI, as 0.5 is often larger than red reflectance values (Qi et al. 1994). When *L* equals zero, SAVI is the same as NDVI. A weakness of SAVI is that it is contingent on the slope of the soil line being equal to one, which in many cases, is not true (Fox et al. 2004). In general, SAVI may be preferable over NDVI with sparsely vegetated surfaces, while NDVI typically works sufficiently well in more densely vegetated surfaces (Qi et al. 1994).

Qi et al. (1994) developed a modified SAVI (MSAVI), where they replaced the constant *L* in SAVI with a variable *L* function, hoping to increase the vegetation dynamic response relative to SAVI and minimize soil noise relative to NDVI. They aimed to develop an automated method for calculating *L* that would cause it to increase with vegetative cover. To achieve this, Qi et al. (1994) used two other VI, NDVI and weighted difference VI (WDVI) that are affected in background soil in opposite ways with dark or wet soils resulting in higher NDVI values and lower WDVI values than light or dry soils with identical amounts of vegetation. Transformed soil adjusted vegetation index (Baret and Guyot 1991) is, in certain ways, an improvement over SAVI in that it takes the specific slope and intercept of the soil line into account.

Relative to NDVI and RVI, indices such SAVI, MSAVI, and TSAVI substantially reduce the variation caused by variability in background soil reflectance (Baret and

Guyot 1991). The difficulty with these indices however, is that some, namely TSAVI require that the parameters of the soil line be known for every soil where the index is being applied, and others, like MSAVI start to become mathematically complex. While Fox et al. (2004) describe a systematic and reasonably straightforward method for determining the soil line, identifying different soil lines within the same image, not to mention the same field, can prove difficult. Despite the many VI proposed over the years, RVI and NDVI remain the most versatile and, at least in the case of NDVI, most widely used today.

2.5 REAL-TIME SENSOR BASED VARIABLE RATE FERTILIZER APPLICATIONS

More recently, active, ground-based sensors that measure reflectance in much the same manner as passive sensors, have been developed and made commercially available. Because they utilize their own light source, active sensors function under any light conditions, even in complete darkness. Two examples of such sensing systems are the GreenSeeker^{TM} (NTech Industries Inc.) and the Crop Circle^{TM} (Holland Scientific). A unique attribute of the GreenSeeker^{TM} is that it can be readily integrated with application equipment to direct variable rate PE N applications in real time. The ability to integrate sensing and application technology is a major development for site specific management as it eliminates the need for acquiring and interpreting images, delineating management zones, and developing fertilizer prescription maps, all of which are specialized tasks that are beyond the scope of most producers. This type of system functions in the absence of GPS, but if mapping is required, then GPS is also required.

2.5.1 Current Sensing Equipment

Both the GreenSeeker^{TM} and the Crop Circle^{TM} sensing systems generate light in pulses and filter out sunlight by only measuring the NIR and visible light reflected off the canopy in pulses. The GreenSeeker^{TM} emits energy from separate diodes in surges that alternate between visible and NIR, with each surge consisting of about 40 individual pulses. The Crop Circle^{TM} emits and measures both visible and NIR bandwidths simultaneously (James Schepers, personal communication). The two differ slightly in the bandwidths that they utilize with the Crop Circle^{TM} (red/NIR) measuring reflectance of spectra at 650 and 890 nm and the GreenSeeker^{TM} (red/NIR) at 671±6 nm and 780±6 nm. The Crop Circle^{TM} is also available with a yellow visible (590 nm) light source, while the GreenSeeker^{TM} is available with a green visible (550±12.5 nm) light source. The Crop Circle^{TM} sensor functions normally as long as the sensor is within 25 – 213 cm from the crop canopy while the recommended distance from the canopy for the GreenSeeker^{TM} is 81 – 122 cm.

2.5.2 Sensor-Based Nitrogen Fertilizer Management

In is arguable that there are many possible ways to manage N using active optical sensors and the preferred approach will certainly vary from one producer to the next depending their specific soil/climate conditions and economic considerations. Nonetheless, there are a few key requirements that should be a part of any sensor-based N management strategy. In general, the objective of this type of strategy is to better match N fertilizer rates with crop demands by simultaneously addressing spatial and temporal variability in both grain yield potential and the N supplying power of the soil. Using this technology to help make better decisions regarding N management does not necessarily require modern application equipment with variable rate capabilities. More than anything else, what is required is the willingness of producers to challenge the way they approach N management on their farms. From a management perspective, the general properties of sensor-based N management strategies include potentially reducing N rates at seeding (there are different ways of approaching this), monitoring the N status of their crops closely both visually and using the sensors, and finally, correcting any N deficiencies early enough for the crop to respond to the applied N.

Very briefly, estimating fertilizer N requirements using ground-based, active sensors may be broken down into three steps. First, estimate the yield potential of the crop being assessed using sensor readings and empirical relationships. Second, in the same manner, estimate the yield potential of the crop growing in the environment not limited by N. Finally, if there is evidence of an N deficiency, determine the magnitude of the deficiency and make a decision as to whether or not to apply N. If no evidence of an N deficiency exists, then no action is required. Better matching N fertilizer rates with crop requirements should result in increased NUE and hopefully profitability either by maintaining grain yields with less fertilizer N or by increasing yields with PE N when there is opportunity to do so.

For producers interested in using sensors to better match their N application rates with crop requirements, the first and most important step is establishing reference areas where N is not limiting in every field. How much N should be applied to the reference area will vary from one producer to the next, as there may be several different approaches to using these sensors. A general rule of thumb is to make sure that N is abundant enough that it does not become limiting during the growing season, but not so excessive that there is potential to harm the crop. Depending on the method of application, more than one application may be required to ensure sufficient N availability in the N-rich reference without reducing plant stands. One possible method for deciding how much N to apply to the reference area is to apply 125 – 150% the amount of N that the producer would normally apply to the crop for a field.

For the rest of the field, apply a reduced quantity of N fertilizer at or prior to seeding, and start monitoring the vegetative growth of this crop relative to the reference area shortly after the crop emerges. Again, how much N should be applied to the majority of the field will vary from one producer to the next, possibly ranging from zero – 100% of normal application rates. Even producers who do not wish to cut back on N rates at or before seeding may benefit from establishing non-N limiting reference areas and making a second application if a response is expected based on the readings of the optical sensor. Alternatively, producers may choose not to apply any N fertilizer to their crops at seeding and apply the entire amount of N post-emergent, if necessary, which may be a viable option in regions or fields where crops do not consistently respond to N. In western Canada, however, we would not generally recommend applying the entire amount of fertilizer N post-emergent as doing so could result in severe yield penalties in dry years (Holzapfel et al. 2007). Applying 50 – 67% of expected N requirements at seeding and potentially applying the remainder post-emergent should be a lower risk alternative to withholding all fertilizer N for a post-emergent application in regions where mid – late season moisture availability is frequently limited (Lafond et al. 2007).

The ratio of the NDVI of the crop in the N-rich environment to that of the crop in the potentially N limiting environment is an indication of the potential difference in YP of the two crops in their current environments (Raun et al. 2002; Mullen et al. 2003). For winter wheat at Feekes growth stage five, Mullen et al. (2003) showed that the ratio of NDVI measurements of winter wheat growing in two contrasting fertility environments was linearly related to the ratio of the grain yields of the two crops (R^2=0.56). By Feekes growth stage 9, the relationship had improved substantially (R^2=0.77). Without much success, Hodgen et al. (2005) attempted to eliminate the need for NR references by using NDVI measurements from crops growing in areas with naturally occurring differences in apparent soil N availability to estimate potential responsiveness to PE N. The major problem with this approach is that many factors other than N availability affect crop growth and it is difficult to isolate areas where N availability is the sole cause of variability.

Because differences in N response are often visible to the naked eye during the vegetative growth stages, N rich references can be a powerful tool even without the use of optical sensors. Raun et al. (2005a) proposed a system where they applied N in increasing increments to a representative area of the field, and identified the optimal N rate as the lowest rate where no visual difference was observed between it and the highest rate. The ratio of the height of winter wheat plants at Feekes 4 – 6 growing under high and low N fertility environments is also well-suited for estimating differences in YP (R^2=0.71; Hodgen et al. 2005). Such methods may be suitable for producers who are hesitant to invest in sensing systems and variable rate equipment, but would still like to consider innovative ways to manage N more effectively. However, the actual rates of N required will depend on the absolute difference in YP between the crop in its current environment and the same crop if any N deficiencies were immediately corrected (Raun et al. 2005b).

Estimating a crop's YP using sensor measurements requires large amounts of previously acquired empirical data to which the measurements can be correlated. However, VI on their own are not particularly useful for estimating yield potential because they constantly change as the growing season progresses (Martin et al. 2007). To be a useful predictor of YP, VI must be normalized to account for differences in plant growth within the specified growth stages. In their early work with winter wheat, Raun et al. (2001) divided the sum of NDVI measurements collected at two separate times by the cumulative GDD between the two sensing dates to estimate YP. Using the resultant index, they explained 50% of the variability in winter wheat yields over nine locations in Oklahoma and two growing seasons. Removing the site-years where abnormal post-sensing conditions affected grain yield improved the relationship substantially (R^2=0.83). In later years, researchers at Oklahoma State University (OSU) modified their methods so that only one NDVI measurement was required, which was subsequently divided by the number of days between planting and sensing where GDD was greater than zero degrees Celsius (Lukina et al. 2001; Raun et al. 2002). While NDVI tends to increase as crops progress through the vegetative growth stages (Martin et al. 2007), dividing the values by a factor such as days or cumulative GDD can substantially reduce these effects and increase the window over which it is possible to estimate YP (Lukina et al. 2001; Raun et al. 2002; Teal et al. 2006). While Teal et al. (2006) did not find that GDD greatly improved the correlation between NDVI and corn yield compared with days from planting, it lengthened the window during which YP could be estimated by two leaf stages and would likely broaden the range of climatic conditions over which the curve could be applied.

Using estimates of a crop's YP and potential responsiveness to fertilizer N to estimate its fertilizer N requirements entails applying these estimates in an N application algorithm. Raun et al. (2005b) describe the N application algorithms developed at OSU in detail. In short, the algorithms estimate the N requirements of the crop at its current yield potential and at its maximum YP if any deficiency in N were immediately corrected and calculates how much N is required to make up the difference. The quantity of PE N that is required depends on the absolute difference in estimated YP of the two crops growing under different N fertility and the expected efficiency of applied N.

While the technology is still relatively new, there is mounting evidence that active optical sensing technology has potential to increase both NUE and profitability of crop production. Using sensor-based estimates of winter wheat YP and N response to determine PE N rates and deferring the entire amount of N until mid-season, Raun et al. (2002) increased grain yields by 273 kg ha^{-1} compared to a similar uniform N rate (43.1 versus 45 kg N ha^{-1}) applied mid-season. Moreover, the same variable rate treatment yielded approximately the same as a uniform treatment that received a uniform rate of 90 kg N ha^{-1} mid-season, but with nearly 47 kg ha^{-1} less fertilizer N (Raun et al. 2002). Due to enhanced grain yields, the treatment that resulted in the highest revenues received 45 kg N ha^{-1} pre-plant plus a variable rate application mid-season. Estimated economic margins in this treatment were more than $9.00 US ha^{-1} higher than any of the other treatments that were evaluated, despite using 17.5 kg N ha^{-1} more than the 90 kg N ha^{-1} uniform rates. The treatments that received variable rate applications of N using the sensor had equal or greater NUE than those with uniform N rates (Raun et al. 2002). Using similar methods in irrigated spring wheat, Ortiz-Monasterio and Raun (2007) reported increases in net returns of \$62 ha^{-1} by using optical sensors and N-rich references to determine PE N rates.

A considerable amount of research is required before producers in western Canada will be able to use this technology to its full potential. To the best of our knowledge, this approach to managing N fertilizer has not been previously documented in western Canada for canola, despite this crop's relatively high N requirements and economic importance. For Canadian producers to adopt this technology and overall approach to N fertilizer management, N application algorithms must be developed for Canadian crops under Canadian environmental conditions. Furthermore, for producers to consider adopting sensor-based N management strategies, research must demonstrate that it will be beneficial for them to do so.

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3.0 ESTIMATING CANOLA (*BRASSICA NAPUS* L.) YIELD POTENTIAL USING OPTICAL SENSORS AND METEOROLOGICAL MEASUREMENTS

3.1 ABSTRACT

There are important agronomic and management benefits to having an objective and reliable method of estimating the potential grain yield in crops early in the growing season. The objective of this study was to determine the feasibility of estimating canola (*Brassica napus* L.) yield potential (YP) using optical sensor measurements early in the growing season and to propose empirical equations for doing so. Nitrogen rate by seeding rate experiments with canola were established in 2005 and 2006 at Brandon, Indian Head, Ottawa, Scott, and Swift Current in order to establish plots with a wide range of potential yields. Each plot's normalized difference vegetation index (NDVI) was measured at various times throughout the growing season using handheld optical sensor and the exponential relationships between NDVI and grain yields were determined. The correlation between NDVI and grain yield was typically very weak until after the canola had developed four leaves and subsequently improved as the season progressed. Coefficients of determination usually peaked when the canola was between the late bolting stage and the start of flowering and became weak when the canola went into full bloom. When NDVI data from selected site-years that was collected when the canola was between the five-leaf stage and early flowering was combined, the exponential NDVI-yield relationship had an R^2 of 0.444. Dividing NDVI by the number of days from planting increased the R^2 to 0.474, thus improving our ability to estimate canola yields with NDVI. All of the heat units evaluated performed similarly to one another and all were a substantial improvement over NDVI on its own and divided by days from planting ($R^2 = 0.528 – 0.562$). In conclusion, while it is possible to estimate

canola yields using NDVI, the NDVI data must be collected when the canola is between the five-leaf stage and early flowering, with the likelihood of obtaining a reliable YP estimate increasing with growth stage. While dividing NDVI by the various heat units heat units was preferable for estimating canola yield, days from planting worked reasonably well and should be considered a viable option if temperature data is not available.

3.2 INTRODUCTION

The potential grain yield of crops such as canola is the culmination of the relationships between numerous abiotic and biotic factors. Such factors include nutrient availability (Grant and Bailey 1993; Karamanos et al. 2005), genetics (Karamanos et al. 2005; Brandt. et al. 2007), plant establishment (Angadi et al. 2003; Brandt et. al. 2007), water availability (Brandt and McGregor 1997), and temperature (Angadi et al. 2000; Morrison and Stewart 2002). While management affects some of these factors, such as soil fertility and genetics, water availability and growing season temperatures are beyond the control of producers. Note than whenever we refer to YP in this manuscript, we mean the yield that can be reasonably expected from a crop growing in its present environment. This is contrary to the definition favoured by plant breeders where YP is the maximum yield of a crop growing in climates to which it is adapted with water and nutrients not limiting (Evans and Fischer 1999).

Adequate fertility levels are critical for sustaining crop growth and canola yields can be limited when any single nutrient is not available in sufficient quantities (Grant and Bailey 1993). Approximately 126, 65, 104, and 25 kg ha^{-1} of N, P_2O_5, K_2O, and S, are required to produce a 2000 kg ha^{-1} canola crop (Manitoba, Agriculture, Food and Rural

Initiatives 2001) and N and P are the predominant nutrients applied as fertilizer in western Canada (Korol 2002). High yielding canola varieties in western Canada often require N fertilizer rates exceeding 100 kg N ha^{-1} to reach maximum yield (Karamanos et al. 2005; Malhi et al. 2007). Canola also responds well to P fertilization, with rates between 20 – 40 kg P_2O_5 ha^{-1} often required to maximize yields (Karamanos et al. 2005). McKenzie et al. (2003) reported positive yield responses to P fertilizer in 45% of 108 different fields located throughout Alberta's brown, black, and grey soil zones. While yield responses to S fertilizer can be inconsistent, 5 – 10 kg S ha^{-1} is often enough to maximize canola seed yields and the benefits of applying S are substantial in fields where its supply is insufficient (Grant et al. 2004; Malhi and Gill 2006).

Canola cultivars are often broadly categorized into hybrid and conventional varieties, with the majority of the current cultivars grown in western Canada being herbicide-tolerant hybrids. Hybrids normally yield higher than conventional varieties and, as such, remove larger quantities of nutrients from the soil (Karamanos et al. 2005; Brandt et al. 2007; Malhi et al. 2007). In Alberta, Karamanos et al. (2005) found that conventional canola required 125 kg N ha^{-1} of fertilizer N to reach maximum seed yields while 150 kg N ha^{-1} was required for hybrids. Malhi et al. (2007) found that while hybrids yielded higher and provided greater net economic returns than conventional canola cultivars, the yield responses to N fertilizer of the two were similar and, thus the recommended N rates for optimum yield and economic returns should be similar. Either way, the enhanced ability of hybrid canola to extract resources from the soil may have implications for subsequent crops and long-term nutrient management (Karamanos et al. 2005; Malhi et al. 2007).

Seedling mortality can sometimes be high with canola, especially when seeded too deep (Malhi and Gill 2004). Low plant densities can potentially limit grain yields (Angadi et al. 2003; Brandt et. al. 2007); however, canola adapts well to low plant populations through increased vegetative growth (Rood and Major 1984) and similar yields of both dry matter and grain have been achieved for canola growing at densities ranging from 20 – 80 plants m^{-2} (Angadi et al. 2003). Canola's ability to maintain grain yields under decreasing plant densities declines in drought years (Angadi et al. 2003). For example, Angadi et al. (2003) showed that the reduction in canola yield resulting from decreasing plant densities from 40 to 20 plants m^{-2} increased from 20% in normal years to 36% in dry years. Despite canola's ability to adapt to low plant densities, Brandt et al. (2007) found that seeding rates of 2.8 kg ha^{-1} were not usually high enough to maximize yields. Furthermore, high seedling mortality resulted in 5.6 kg ha^{-1} being inadequate 25% of the time (Brandt et al. 2007). By contrast, with relatively low mortality rates, Morrison et al. (1990) found that the optimum seeding rates for canola ranged from 1.5 – 3 kg ha^{-1}.

Prolonged periods of high temperatures can substantially reduce canola seed yields, especially during the reproductive growth stages (Angadi et al. 2000; Morrison and Stewart 2002). Compared with daytime maximum temperatures of 20˚C, seven continuous days with maximum temperature of 35˚C during the early flowering stage reduced canola seed yields by 47% (Angadi et al. 2000). Delaying the same high temperatures to the early pod-filling stage reduced grain yields by 12% compared with the canola grown at moderate temperatures (Angadi et al. 2000). Morrison and Stewart (2002) also found that temperatures during flowering exceeding 29˚C reduced canola yields, which was consistent with Angadi et al. (2000) who observed no reductions in yield at temperatures of 28˚C. High temperatures continue to decrease canola seed yields through seed maturation, primarily due to reduced seed size and weight (Aksouh-Harradj et al. 2006).

Water availability is commonly the major factor limiting canola yields throughout most of the northern Great Plains (Brandt and McGregor 1997; Johnston et al. 2002). Potential evapotranspiration exceeds total precipitation in the majority of the Prairies; thus moisture commonly becomes limited as the growing season progresses (Johnston et al. 2002). It is worth mentioning that certain management practices, such as time of seeding, harvest methods, and tillage practices, can influence moisture availability to a limited extent. Cutforth et al. (2006) found that planting canola into fields over-wintered with tall stubble increased canola yields by 16% and WUE by 11% compared with fields that were cultivated in the fall. Lafond et al. (2006) found that WUE of flax was higher under zero-tillage and minimum tillage systems than in conventional tillage systems. Whether it is better to seed canola early or late in the spring depends on the year. In 2002 at Swift Current, where dry conditions at planting preceded a warm, moist summer, postponing seeding until the end of May resulted in seed yields that were 18% higher than canola seeding in late April (Angadi et al. 2004). Under conditions that are more typical, early seeding enables the crop to make better use of early spring moisture reserves and flower before the daytime temperatures become too hot. Overall, the potential for sound management to increase water availability or use-efficiency in crop production is very limited in our climate and growing season precipitation accounts for the vast majority of water used by crops (Lafond et al. 2006).

The ability to objectively estimate canola YP would potentially allow producers to make better informed decisions with respect to various factors such as fertilizer inputs and crop protection products, how to forward market their crop, and allocating grain storage. However, because of the many factors that affect the yield potential (YP) of canola and difficulties in quantifying the effects of these factors, estimating the potential yield of canola during the growing season is often rather subjective.

Recent improvements in optical sensing technology along with innovative methods of using the technology have potential to improve our ability to estimate the YP of crops in an objective manner. The GreenSeeker^{TM} (NTech Industries) and the Crop Circle^{TM} (Holland Scientific) are two ground-based, active optical sensors that are commercially available and have several advantages over satellite-mounted, passive sensors. Unlike satellite-mounted sensors, which require an external light source, clear skies, and synchronization with satellites orbiting patterns, active, ground-based sensors can be used any time of the day, even night, and are unaffected by atmospheric conditions or the position of the sun. Furthermore, the data collected with ground based-sensors is immediately available for use, without the lag-time associated with downloading and processing satellite images. A unique attribute of the GreenSeeker^{TM} is its ability to integrate with application equipment and direct variable rate applications of agrochemicals in real time. Combined with global positioning systems, these sensing systems offer a relatively simple, cost effective method for producers to map the variability of their fields with minimal effort every time they spray. These high-resolution maps could subsequently be used for such purposes as delineating management zones as a basis for applying variable rates of crop inputs (Basnyat et al. 2005).

First introduced by Rouse et al. (1974), normalized difference vegetation index (NDVI) is the most widely used vegetation index calculated with these sensors. The GreenSeeker^{TM} sensor calculates NDVI using Equation 3.1:

$$\mathrm{NDVI} = (\rho_{\mathrm{nir}} - \rho_{\mathrm{red}}) \;/\; (\rho_{\mathrm{nir}} + \rho_{\mathrm{red}}) \qquad [3.1]$$

where ρ_{nir} and ρ_{red} are the fractions of emitted NIR and red visible light reflected off the crop canopy respectively.

However, the NDVI of crops changes over the course of the season, however, typically increasing through the vegetative growth stages, levelling off and peaking during the reproductive stages, and decreasing to a certain extent as the crop approaches maturity (Martin et al. 2007). Despite this temporal variability, NDVI measurements collected during the appropriate crop growth stages are capable of detecting relative differences of various crop parameters. Moges et al. (2004) showed that NDVI measurements of winter wheat canopies collected between Feekes growth stages four and 10 increase exponentially with forage biomass and N uptake. Similarly, Freeman et al. (2007) observed an exponential correlation between NDVI and both biomass yield and N uptake of individual corn plants. However, the best correlations resulted when biomass and N yields of the individual plants were expressed on an area basis, suggesting that NDVI is better suited for drawing inferences regarding whole crop canopies than for individual plants (Freeman et al. 2007).

Because of the relationship between early season crop growth and grain yields, strong correlations between NDVI and grain yields have been reported for a variety of crops (Ma et al. 2001; Raun et al. 2002; Teal et al. 2006). Ma et al. (2001) found that the NDVI of soybean canopies at the R2, R4, and R5 stages were well correlated with grain yields, further noting that the best relationships occurred at the later sensing dates and that the relationship between NDVI and soybean yield was not affected by variability in plant populations. However, for NDVI to be used to estimate YP, empirical information is required to convert the measurements to grain yield and NDVI must first be normalized to account for the temporal changes that occur as the crop develops (Martin et al. 2007). Raun et al. (2001) accounted for up to 83% of the variability in winter wheat grain yields using the sum of two post-dormancy NDVI measurements divided by the number of growing degree days (GDD) accumulated between the two measurements. These methods were further refined so that only one NDVI value, which was subsequently divided by the number of days between planting and sensing where GDD was greater than zero, was required to estimate the potential yield of winter wheat (Lukina et al. 2001; Raun et al. 2002). Because NDVI is an indirect measure of biomass (Moges et al. 2004), when it is divided by a factor like days from planting, the quotient is essentially a growth rate that is often more closely related to grain yield than the original values (Raun et al. 2002). In this manner, Teal et al. (2006) estimated corn YP using NDVI measurements and, in addition to dividing NDVI by days from planting, they tried GDD as a potential divisor. While normalizing NDVI using GDD did not greatly improve the relationship with corn yield over days from planting, it lengthened the window over which the equation could be applied by two leaf stages and would conceivably allow the model to be applied in an increased range of climates (Teal et al. 2006). To the best of our knowledge, the suitability of NDVI for estimating canola YP has not been yet been evaluated, despite this crop's economic importance.

The objectives of this study were to establish the relationships between canola yield and NDVI over the growing season and determine the best growth stages and methods to estimate canola YP using optical sensors and to develop empirical equations for doing so.

3.3 MATERIALS AND METHODS

3.3.1 Site Descriptions

Field experiments with small plots of canola were completed in 2005 and 2006 at Agriculture and Agri-Food Canada (AAFC) locations at Brandon, Indian Head, Ottawa, Scott, and Swift Current. Brandon is located in southwest Manitoba in the Black soil zone (Lat. 49˚75'N, Long. 99˚48'W) and the soil is a Newdale clay loam (Orthic Black Chernozem). On average, Brandon receives 474 mm of precipitation each year and has a mean temperature of 2.4˚C. Indian Head (50˚33'N, 103˚39'W) lies in the thin Black soil zone of Saskatchewan and the soil type is an Indian Head heavy clay (Rego Black Chernozem). The mean annual temperature at Indian Head is 2.6˚C and the average amount of precipitation received each year is 447 mm. Scott, SK is in the Dark Brown soil zone (52˚21'N, 108˚49'W) and the soil type is an Elstow loam (Orthic Dark Brown Chernozem). Scott receives an average of 359 mm of rain annually and has a mean annual temperature of 1.9˚C. Swift Current, the driest of the sites, is in the Brown soil zone of Saskatchewan (50˚16'N, 107˚44'W) and the soil is a Cypress light loam (Rego Brown Chernozem). While the mean annual precipitation at Swift Current of 349 mm is similar to that at Scott, the mean annual temperature (3.9˚C) and overall potential evapotranspiration is higher at Swift Current. Ottawa is in southeast Ontario (45˚ 23′ N, 75˚ 43′ W) and has a humid continental climate that is relatively warm and wet compared to the western locations. Ottawa receives an average of 914 mm of precipitation annually and the mean annual temperature is 6.3˚C. The soil at Ottawa is a North Gower clay loam (Humic Gleysol).

3.3.2 Experimental Design and Crop Management

The treatments were a factorial combination of six N fertilizer rates and four seeding rates. The N fertilizer rates applied were 0, 25, 50, 100, 150, and 200 kg N ha^{-1} and the seeding rates were 25, 50, 100, and 200 viable seeds m^{-2}. The purpose of varying N fertilizer rates and seeding rates was to establish canola plots with the widest range of YP as possible within each site-year. Furthermore, including seeding rate as a treatment ensured that our results would apply over a wide range of canola plant populations. The plots were arranged in a randomized complete block designs (RCBD) with four replications at all site-years except Ottawa in 2006 where one replicate was lost due to excessive moisture.

We targeted seeding for early – mid May and the actual seeding dates ranged from May 6 to May 19 (Table 3.1). The cultivar used was InVigor^{TM} 5020 at all site-years except for Ottawa in 2006 where a glyphosate tolerant variety (cultivar unknown) was used. Competition from weeds and volunteer crops was minimized using registered herbicides at the recommended crop and weed growth stages and the specific products used varied from one site-year to the next (Table 3.1). Canola was planted directly into standing cereal stubble and the fields were continuously cropped at all sites except for Swift Current where the plots were planted into chem-fallow and Ottawa where the plots were tilled prior to seeding. The seeder at Brandon was equipped with 12 disc openers spaced 25 cm apart through which the canola seed was placed. At Indian Head and Scott, the canola was seeded using two high clearance hoe press drills equipped with double-offset discs placed mid-way between every second opener. Seed rows at Indian Head were spaced 20 cm apart, while at Scott the seedrows were spaced 25 cm apart. The plots at Swift Current were seeded using a self-propelled air seeder equipped with eight Stealth^{TM} (CNH America LLC) side-band openers spaced 23 cm apart. At Ottawa, the plots were seeded using a six-row Hege seeder with a cone splitter, adjustable depths, and 20 cm seedrow spacing. An error at the time of seeding at Scott 2005 resulted in ten times the targeted number of viable seeds planted, thus 25 seeds m^{-2} became 250 seeds m^{-2}, 50 seeds m^{-2} became 500 seeds m^{-2}, and so on. Consequently, plant density data from this site was not included in the analysis and we excluded the effects of seeding rate from the model during analysis.

Granular urea at Brandon was placed in a mid-row band at seeding along with monoammonium phosphate. At Indian Head, granular urea and 25 kg P_2O_5 ha^{-1} as triple super phosphate were placed in the mid-row band and 15 kg P_2O_5 ha^{-1} as triple super phosphate placed in the seedrow. At Scott, urea fertilizer was placed in the mid-row band and a granular blend of triple super phosphate, potassium chloride, and ammonium sulphate was seed placed. Urea at Swift Current was side-banded approximately 2.5 cm beside and 2.5 cm below the seed and triple super phosphate was seed placed. Adequate S fertility at Brandon, Indian Head and Swift Current was ensured by broadcasting potassium sulphate prior to seeding. At Ottawa, N was supplied as granular ammonium nitrate and P and K were supplied as triple super phosphate and potassium chloride. All fertilizer at Ottawa was hand broadcast on the soil surface and the KCl rate supplied 25 kg K_2O ha^{-1} in 2005 and 20 kg K_2O ha^{-1} in 2005. The fertilizer applications at Ottawa took place four and five days after seeding in 2005 and 2006 respectively. The total quantities of P and S applied as fertilizer at each site-year appear in Table 3.1.

Table 3.1. Selected agronomic information for canola N rate by seeding rate studies at Brandon, Indian Head, Ottawa, Scott, and Swift Current in 2005 and 2006.

Site	Year	Seeding date	Res. NO_3-N	P_2O_5 applied	S applied	In-crop Herbicide	Swath Date	Harvest Date
			kg ha^{-1}					
Brandon	2005	May 17	35	16	15	Jun 11 (500g glufosinate ammonium ha^{-1} + 15 g clethodim ha^{-1}	Aug 20	Sep 7
	2006	May 10	45	16	15	May 25 (113g clethodim ha^{-1}) Jun 4 (500g glufosinate ammonium ha^{-1} + 15g clethodim ha^{-1}	Aug 11	Aug 21
Indian Head	2005	May 11	35	40	15	Jun 3 (196g clopyralid ha^{-1}) June 6 (500g glufosinate ammonium ha^{-1} + 15g clethodim ha^{-1}	Aug 30	Sep 6
	2006	May 15	43	40	15	Jun 23 (500 g glufosinate ammonium ha^{-1} + 15 g clethodim ha^{-1})	Aug 10	Aug 29
Ottawa	2005	May 6	na	25	0	Jun 8 (300 g glufosinate ammonium ha^{-1}+175g fluazifop-p-butyl ha^{-1})	na	Aug 4 - 5
	2006	May 11	na	20	0	Jun 6 (450g glyposate ha^{-1})	na	July 27
Scott	2005	May 19	34	14	6	June 16 500 g glufosinate ammonium ha^{-1}	n/a	Sep 30
	2006	May 18	40	12	5	June 13 500 g glufosinate ammonium ha^{-1}	n/a	Aug 23
Swift Current	2005	May 9	7	25	20	June 16 371 g glufosinate ammonium ha^{-1}	Aug 10	Aug 29
	2006	May 16	11	25	20	June 19 300 g glufosinate ammonium ha^{-1}	Aug 4	Aug 21

n/a – not applicable

Canola at Brandon, Indian Head and Swift Current was swathed when between 30 – 60% of the seeds had changed color and at all other sites the plots were straight-cut at maturity. At Indian Head and Brandon, the whole plots were harvested while only the inside rows were harvested at Scott and Swift Current. At Ottawa, six 1 m rows were hand-harvested, dried for seven days at 30˚C, and mechanically threshed using a stationary combine. Canola seed at Indian Head, Scott, and Swift Current was harvested mechanically at maturity using Wintersteiger^{TM} (Wintersteiger AG) plot combines, while a Massey Ferguson MF – 8 (AGCO Corporation) plot combine was used at Brandon. Dates of all harvest operations appear in Table 3.1.

3.3.3 Crop Measurements

The specific data collected varied from one site-year to the next, but the following core data were collected in all cases. Average plant densities were determined for each plot by counting the number of plants in either two or four 0.5 – 1 m seed rows and calculating the number of plants m^{-2}. Grain yields were determined by cleaning the harvested grain samples if necessary, determining their mass, correcting the weights to 10% seed moisture content and converting the yields from each plot to kg ha^{-1}. Finally, the mean NDVI of each plot was determined repeatedly over the course of the growing season using handheld model 505 GreenSeeker^{TM} sensors.

These sensors emit electromagnetic radiation in two separate bandwidths, which are approximately 25 nm wide and centered at 656 nm (Red) and 774 nm (NIR) and measure the reflectance of the emitted bandwidths off the crop canopy. The sensor's field of view is approximately 60 cm wide by 10 cm deep and each plot was measured across its entire length with the sensor head positioned 0.8 – 1.2 m above the crop canopy. The average NDVI from each plot within a sensing date was recorded electronically. In the winter of 2005/2006, we returned all of the sensors to the manufacturer for recalibration. Prior to analysis, we adjusted the data collected in 2005 according to specific calibration equations for each sensor provided by the manufacturer (data not shown). The equations were derived from NDVI measurements of standard surfaces before and after sensing, thus were intended to correct the previously recorded measurements to the calibrated NDVI values. We applied no adjustments to the NDVI data collected in 2006. The specific dates that the crops were sensed at each location are included in Tables 3.2 through 3.6 in the next section.

In addition to the plant density, yield, and NDVI data, several additional variables were measured at the specified site-years only. Aboveground canola biomass yields (kg ha^{-1} dry matter) were determined when the crop was at the early – mid flowering stage at Indian Head and Scott in 2005 and 2006 and at Brandon in 2006. After weighing the dried biomass samples, we ground the samples to fit through 2 mm screens using Wiley mills and analyzed the samples for total Kjeldahl N content (g N kg $biomass^{-1}$). For the site-years where biomass and plant N were determined, we estimated in-season N uptake by multiplying the observed biomass yield by g N g $biomass^{-1}$. Grain N content (g N kg $grain^{-1}$) was determined for each plot at all site years except Ottawa in 2006 and the Kjeldahl method was used in all cases except for Scott in 2005 where an NIR analyzer was used (Daun et al. 1994). We also calculated the total quantity of N removed in the canola seed (kg N ha^{-1}) for each plot by multiplying g N g $grain^{-1}$ by grain yield. Finally, fall soil residual NO_3-N concentrations were determined after harvest at Indian Head in both years and Scott in 2006. At Indian Head in 2005 and Scott in 2006, soil samples were collected in each plot for the zero to 60 cm soil depth and samples from a single core at Indian Head and two combined cores at Scott were submitted for analysis. At Indian Head in 2006, we sampled fewer plots more intensively; combining three soil cores for each plot at two separate depths, zero to 60 cm and 60 – 120 cm. Rather than sampling every plot at Indian Head 2006, we sampled all of the N rates within the 100 seeds m^{-2} seeding rate only. While the results from these additional crop measurements are excluded from this manuscript, summary tables for kg ha^{-1} biomass yield, plant N content, N uptake, grain N, kg grain N ha^{-1} removed, and fall residual soil NO_3-N are presented in Appendix A.

3.3.4 Meteorological Data and Calculation of Heat Units

All heat units were calculated using Excel 2003 (Microsoft Corporation) with the daily minimum and maximum temperatures for each site acquired from Environment Canada's online climate data (Environment Canada 2007). We tested four separate heat units as potential normalizing values for NDVI. These included growing degree-days with base temperatures of zero and 5˚ C (GDD_0 and GDD_5 respectively), corn heat units (CHU), and physiological days (P-days). We also considered the number of days from planting as a potential normalizing value. Equations 3.2 and 3.3 were used to calculate GDD and CHU respectively:

$$GDD = (T_{max} + T_{min}) / 2) - T_b \qquad [3.2]$$

$$CHU = 0.9(T_{min}-4.4)+1.665(T_{max}-10)-0.042(T_{max}-10)^2 \qquad [3.3]$$

where T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature and T_b is the base temperature.

Corn heat units are often considered an improvement over GDD in that they assume a nonlinear crop response to increasing temperatures and different base temperatures for day and night. Physiological days (P-days; Sands et al. 1979) are similar to CHU in that they assume a non-linear response to temperature but differ in that P-days assume different crop responses for different ranges of temperatures as they occur over the course of the day, which are estimated from the minimum and maximum daily temperatures. For canola, the suggested base temperature is 5°C, the optimum temperature is 17°C and the maximum is 30°C (Wilson 2002). Daily P-days were calculated using equation 3.4:

$$\text{P-Days} = 1/24 * [5 * P(T_1) + 8 * P(T_2) + 8 * P(T_3) + 3 * P(T_4)] \qquad [3.4]$$

where T_1 is the minimum daily temperature (T_{min}), $T_2 = [(2 * T_{min}) + T_{max}] / 3$, $T_3 = [T_{min} + (2 * T_{max})] / 3$, and T_4 is the maximum daily temperature (T_{max}). Two separate quadratic equations describe the relationship between P and crop growth from the base temperature to the optimum and from the optimum to the maximum, while no growth is assumed for periods where temperatures are below the minimum or above the maximum. Equations 3.4 through 3.7 describe the P functions used to calculate P-days in this study:

$$P = 0 \qquad \text{when } T < 5^\circ\text{ C} \qquad [3.5]$$
$$P = k * \{1 - [(T-5)^2 / (17-5)^2]\} \qquad \text{when } 7 <= T < 17^\circ\text{ C} \qquad [3.6]$$
$$P = k * \{1 - [(T-17)^2 / (30-17)^2]\} \qquad \text{when } 17 <= T < 30\ ^\circ\text{ C} \qquad [3.7]$$
$$P = 0 \qquad \text{when } T >= 30^\circ\text{ C} \qquad [3.8]$$

where k is scale factor set at a value of 10.

3.3.5 Data Analysis

Data for plant density, grain yield, and the parameters summarized in Appendix A were analyzed using the general in linear model (GLM) procedure of SAS 9.1 (SAS Institute, Inc.), with a separate analysis completed for each site-year. Separate means for each of the N rate by seed rate combinations appear in Appendix A for the site-years where there was a significant interaction between the two factors. Treatment means for the main effects were separated according to Ryan-Einot-Gabriel-Welsch's (REGWQ) multiple range test which controls the experimentwise error. The reason for including the multiple range tests was as to help identify threshold levels where crop responses to increasing levels inputs no longer occurred. Orthogonal contrasts describe the various crop responses to N fertilizer and seeding rates.

The relationships between NDVI and canola yield were analyzed using the non-linear regression procedure in SigmaPlot 10 (Systat Software Inc.), with two parameter exponential equations used for all analyses and the coefficient of determination (R^2) used to determine the relative goodness of fit. Previous work has established that exponential equations more accurately describe the relationship between most vegetation indices and crop parameters than linear equations (Broge and Mortenson 2002). In similar studies, Raun et al. (2001 and 2002) also used a two parameter exponential equation to estimate winter wheat yields with NDVI. The relationship between NDVI and grain yield was first established separately for each of the sensing dates at each site-year to determine if and at what growth stages it was possible to estimate canola YP with NDVI. Next, we compiled all of the NDVI measurements from the selected range of growth stages and divided them separately by each of the potential normalizing values. The normalized NDVI values were then plotted against grain yield and the best-fitting two-parameter exponential curves determined, with R^2 used to determine the relative performance of the different potential divisors. While SigmaPlot (Systat Software Inc.) provided p-values for all of the regressions, these values are not reported because all for all exponential equations where the adjusted R^2 was 0.100 or higher the p-values were less than 0.001. As such, these values are not very meaningful and standard errors of the parameter estimates are reported instead.

3.4 RESULTS AND DISCUSSION

3.4.1 Growing Season Conditions

Monthly temperature and precipitation data for the 2005 and 2006 growing seasons at the field sites are summarized in Table 3.2 and daily accumulation of GDD_0, CHU, and P-days and daily precipitation appear in Appendix C. Overall, growing season conditions in 2005 were cooler and wetter than in 2006 at Brandon, Indian Head, Scott, and Swift Current, but not at Ottawa. At Ottawa, temperatures were close to normal both years and precipitation was below normal in 2005 and slightly above normal in 2006. Overall, moisture conditions in 2005 were considered excellent at Indian Head and very wet at Brandon and Scott, with the latter two sites receiving 183 mm and over 200 mm more growing season precipitation respectively than normal. In 2006, conditions were warmer and drier than average at Brandon and Swift Current and very dry at Indian Head where only 18 mm of precipitation fell in July and August combined. While total rainfall at Scott in 2006 was close to average overall, July was hotter and drier than normal.

Table 3.2. Mean monthly temperatures (˚C) and total precipitation levels (mm) for 2005 and 2006 growing seasons and 30 year averages at Brandon, Indian Head, Ottawa, Scott, and Swift Current.

	Mean Monthly Temperature			Growing Season Precipitation		
Month	**2005**	**2006**	**LT^{z}**	**2005**	**2006**	**LT^{z}**
		˚C			mm	
			Brandon			
May	10.0	12.2	11.4	54	41	53
June	17.1	17.7	16.1	255	82	74
July	19.6	20.5	18.4	129	8	76
August	17.1	19.3	17.5	17	76	69
Avg. / Total	**16.0**	**17.4**	**15.9**	**455**	**207**	**272**
			Indian Head			
May	8.8	11.1	11.4	58	39	56
June	14.8	16.0	16.1	99	80	79
July	16.9	17.9	18.4	59	6	67
August	15.5	17.3	17.5	98	12	53
Total	**14.0**	**15.6**	**11.4**	**314**	**137**	**255**
			Ottawa			
May	11.3	14.3	13.6	36	87	81
June	21.0	18.7	18.4	96	107	91
July	21.9	22.0	21.0	84	90	89
August	21.1	19.1	19.7	68	99	88
Total	**18.8**	**18.5**	**18.2**	**284**	**383**	**349**
			Scott			
May	9.2	10.9	10.9	41	63	36
June	13.4	15.2	15.2	100	67	63
July	16.2	19.4	17.0	218	35	71
August	13.5	17.4	16.3	89	47	43
Total	**13.1**	**15.7**	**14.9**	**448**	**212**	**213**
			Swift Current			
May	9.7	12.3	11.1	24	35	44
June	14.6	16.2	15.6	99	97	66
July	18.3	21.0	18.1	52	31	52
August	16.4	19.1	17.9	21	21	40
Total	**14.8**	**17.2**	**15.7**	**196**	**184**	**202**

^{z}Canadian Climate Normals: 1971 - 2000

3.4.2 Crop Establishment

The effects of N rate and seeding rate on canola establishment varied from one site-year to the next (Table 3.3). Overall, seedling mortality was lowest at Indian Head in 2005 where the number of plants m^{-2} established exceeded the targeted number of viable seeds m^{-2} at the two lowest seeding rates and, averaged across all of the seeding rates, more than 90% of the viable seeds planted became established plants. In contrast, seedling mortality was highest at Brandon in 2006 where only 22% of the planted viable

Table 3.3 Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on canola plant populations (plants^{-2}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate					plants m^{-2}					
0 kg N ha^{-1}	48	21	80.9	66.6	62.7	49.2a	n/a	51.8	49ab	71a
25 kg N ha^{-1}	41	22	87.0	58.5	64.2	65.2a	n/a	57.4	60a	65ab
50 kg N ha^{-1}	50	21	89.6	59.0	54.7	68.9a	n/a	55.8	49ab	55bc
100 kg N ha^{-1}	40	20	77.4	58.2	70.6	65.2a	n/a	52.9	45ab	45c
150 kg N ha^{-1}	47	19	85.4	57.9	66.3	61.5a	n/a	55.6	36bc	31d
200 kg N ha^{-1}	39	21	91.7	64.3	72.2	52.9a	n/a	49.7	27c	26d
Seed Rate										
25 seeds m^{-2}	15.5d	9d	41d	24c	24d	23.2a	n/a	21.3c	22c	13d
50 seeds m^{-2}	26.2c	13c	66c	38b	48c	39.1b	n/a	32.1c	29c	35c
100 seeds m^{-2}	54.4b	23b	89b	92a	74b	55.0c	n/a	56.1b	45b	61b
200 seeds m^{-2}	80.2a	39a	145a	98a	116a	124.7d	n/a	106.0a	82a	85a
ANOVA ***Source***					p – values					
N-Rate	ns	ns	ns	ns	ns	*	n/a	ns	**	**
Seed-Rate	**	**	**	**	**	**	n/a	**	**	**
N*Seed	ns	ns	ns	ns	*	ns	n/a	ns	ns	**
Replicate	*	**	ns	ns	ns	**	n/a	ns	ns	ns
Res. C.V.	31.9	20.6	20.4	26.8	33.4	28.2	n/a	31.9	34.8	29.5
Contrast										
N-Lin.	ns	ns	ns	ns	ns	ns	n/a	ns	**	**
N-Quad.	ns	ns	ns	ns	ns	**	n/a	ns	ns	ns
N-Cub.	ns	ns	ns	ns	ns	ns	n/a	ns	ns	ns
Seed-Lin.	**	**	**	**	**	**	n/a	**	**	**
Seed-Quad	**	ns	ns	**	*	*	n/a	ns	ns	**
Seed-Cub.	ns	ns	ns	**	ns	ns	n/a	ns	ns	ns

n/a – data not available for this site-year; ns – F-test not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p \leq 0.01$

seeds became established. At the remaining site-years, seedling survival was generally about 50% or higher.

Nitrogen rate did not affect crop establishment at any of the sites except for Swift Current, where in both years the number of plants decreased linearly as the rate of N fertilizer applied was increased. At Ottawa in 2006, the F-test for N rate and plant density was significant ($p = 0.045$) and so was the quadratic orthogonal contrast, but means separations according to the REGWQ procedure did not result in any distinct groupings among the N rates. At Swift Current in 2005, where the effects of N rate on plant density were significant but the N rate by seed rate interaction was not, plant densities decreased linearly and were 55% lower at the 200 kg ha^{-1} N rate than they were at the at the 25 kg ha^{-1} N rate. The observed effects of increasing N rates on crop establishment at Swift Current were attributed to inadequate separation between the seed and urea fertilizer with side-band application at this site (Johnston et al. 2001) and drier overall conditions (Malhi et al. 2003). Johnston et al. (2001) compared canola establishment at varying levels of side-banded N fertilizer and different openers, and found that at 120 kg N ha^{-1}, plant stands were reduced by 19 – 30% with some openers and unaffected with others. Malhi et al. (2003) found that the negative effects of seed-placed urea on canola establishment were more profound under dry conditions, possibly because of reduced crop uptake of the applied N and a greater proportion of the total ammoniacal N existing in the toxic NH_3 form.

As expected, the number of plants established increased as the seeding rate was increased. At all of the site-years, the linear relationship between seeding rate and plant density was highly significant ($p \leq 0.01$). A quadratic relationship was detected at five of nine site-years where the percentage of additional seeds planted that became established to decrease as the seeding rate increased, possibly a result of increased competition between canola plants at the higher seeding rates. At Indian Head in 2006, the cubic relationship between seeding rate and plant establishment was also highly significant, with the greatest increase in plants observed when the seeding rate was increased from 50 to 100 viable seeds m^{-2}.

A significant N rate by seed rate interaction existed for the effects on plant density at Ottawa in 2005 and at Swift Current in 2006. The presence of such an interaction indicates that the effects of N rate on plant density sometimes depended on the level of seeding rate, and vice versa. At Ottawa 2005, the interaction was such that at low N rates, canola plant densities increased linearly while at high N rates plants m^{-2} increased in curvilinear fashion (Table A.1). In contrast, plant densities at Swift Current in 2006 increased linearly and quadratically with seeding rates at very low N rates and linearly when higher N rates were applied (Table A.2).

3.4.3 Grain Yield

The absolute canola seed yields observed varied from one site-year to the next. Averaged across all treatments, the highest canola yield was 3343 kg ha^{-1} at Ottawa in 2005 while the lowest mean yield was 502 kg ha^{-1} at Swift Current in 2006 (Table 3.4). Averaged across all sites, canola seed yields were higher in 2005 than in 2006, presumably a result of increased moisture availability, with the exception of Ottawa. At Ottawa, yields were also higher in 2005; however, excessive moisture was attributed as the principal cause of the lower grain yields observed in 2006.

Table 3.4. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on canola grain yield (kg ha^{-1}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate					kg ha^{-1}					
0 kg N ha^{-1}	1107c	1164a	1839c	1430e	2972b	1806c	1362d	889c	339d	352d
25 kg N ha^{-1}	1714b	1166a	2385b	1654.7d	3124b	2117b	1582c	957c	988c	524abc
50 kg N ha^{-1}	1721b	1181a	2530b	2013c	3385ab	2053b	1680c	1009bc	1337b	612a
100 kg N ha^{-1}	2049ab	1092a	2838a	2420b	3356ab	2288ab	2024b	1243a	1682a	588ab
150 kg N ha^{-1}	2157a	1180a	2937a	2578ab	3320b	2421a	2173ab	1164ab	1664a	501bc
200 kg N ha^{-1}	2187a	1135a	2951a	2629a	3898a	2400a	2361a	1215a	1545a	439cd
Seed Rate										
25 seeds m^{-2}	1485b	823c	2269b	2180ab	2905b	1793d	n/a	1001b	1130	325d
50 seeds m^{-2}	1792a	1122b	2782a	2271a	3370a	2108c	n/a	1036b	1275ab	464c
100 seeds m^{-2}	1977a	1294a	2576a	2083b	3541a	2293b	n/a	1082ab	1234b	544b
200 seeds m^{-2}	2035a	1382a	2692a	1950c	3554a	2530a	n/a	1199a	1398a	673a
ANOVA *Source*					p – values					
N-Rate	**	ns	**	**	**	**	**	**	**	**
Seed-Rate	**	**	**	**	**	**	n/a	**	**	**
N*Seed	ns	ns	ns	ns	ns	ns	n/a	ns	*	ns
Replicate	ns	*	ns	ns	ns	**	ns	ns	**	**
Res. C.V.	22.8	16.2	12.4	8.7	17.3	10.0	13.5	17.0	18.5	21.7
Contrast										
N-Lin.	**	ns	**	**	**	**	**	**	**	ns
N-Quad.	**	ns	**	**	ns	*	ns	*	**	**
N-Cub.	ns	ns	ns	ns	*	ns	ns	ns	**	**
Seed-Lin.	**	**	**	**	**	**	n/a	**	**	**
Seed-Quad	**	**	*	**	**	**	n/a	ns	ns	**
Seed-Cub.	ns	ns	**	ns	ns	ns	n/a	ns	ns	ns

n/a – data not available for this site-year; ns – F-test not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p < 0.01$

At all of the site-years except for Brandon in 2006, canola seed yield increased with the addition of N fertilizer. At Brandon in 2006, for reasons that are not certain, there were no differences in canola seed yield among any of the six N fertilizer rates. Poor quality seed may have partly contributed to the lack of response observed at this site-year and an ethanol vigor test revealed poor seed vigor (data not shown). At the majority of the site years, maximum canola yields were achieved with 100 – 150 kg N ha^{-1}, which is consistent with other studies completed in western Canada (Karamanos et al. 2005; Malhi et al. 2007). The greatest response to N fertilizer occurred at Swift Current in 2005 where the seed yield was increased from 339 kg ha^{-1} in the unfertilized check to 1682 kg ha^{-1} at the 100 kg N ha^{-1} fertilizer rate.

At all of the site-years where there was a yield response to N except for Swift Current 2005, the linear relationship between N fertilizer rate and seed yield was highly significant. In addition, the quadratic relationship between N rate and seed yield was significant at all of the site-years where there was a response to N except for Ottawa and Scott in 2005. At Ottawa, the response to N fertilizer was best described by the cubic contrast whereby the yields of the 50, 100, and 150 kg N ha^{-1} treatments were similar, but grain yield was increased when the applied N rate was increased from 150 to 200 kg N ha^{-1}. Where observed, the quadratic relationship between N rate and seed yield indicated diminishing increases in grain yield as the rate of N was increased. At Swift Current in 2006, N rates exceeding 100 kg ha^{-1} negatively affected grain yield. The cubic relationship was also significant at Swift Current in both 2005 and 2006; however, there was an interaction between the effects of N and seeding rates on grain yield at Swift Current in 2005, thus the results of the orthogonal contrasts for the main effects at this site-year need to be interpreted cautiously. The interaction between N rate and seeding rate was such that increases in seed yield due to N rates beyond 100 kg N ha^{-1} occurred only at the highest seeding rate (Table A.3). Brandt et al. (2007) reported similar results whereby seed yield responses to high rates of seed or fertilizer only occurred when both inputs were at the highest levels.

3.4.4 NDVI versus Canola Seed Yield

The first step taken towards establishing whether it is possible to use NDVI to estimate canola yield was to examine the exponential relationships between NDVI and grain yield at each site-year / sensing date combination and establish the range of growth stages where the two variables were correlated. Parameter estimates and coefficients of determination for each of the sensing dates appear for each site in Tables 3.5 through 3.9 and the relationships between NDVI and canola seed yield for each sensing date at each site-year are presented graphically in Appendix D.

There was no correlation between NDVI and grain yield at Brandon in 2005 for the two earliest sensing dates, at which the canola was between the cotyledon and two-leaf stages (Table 3.5). From June 14 onward, the relationship improved as the crop developed, peaking at R^2=0.629 on July 5 when the crop was just beginning to flower. In 2006 at Brandon, the trends were similar as in 2005, with the relationship between NDVI and grain yield improving as the canola developed, reaching a maximum R^2 of 0.529 on June 26, at the late bolting stage, and weakening from this point onwards.

Table 3.5 Parameter estimates and adjusted^z coefficients of determination for NDVI (x) – yield (y) relationship at various crop stages (Harper and Berkenkamp 1975) for canola plots at Brandon, MB. Values enclosed in brackets are the standard error of the parameter estimates (n = 96).

			Parameter estimates $y = a*\exp(b*x)$		
Year	Date	Crop Stage	*a*	*b*	Adj. R^2
2005	June 3	1 – 2.1	1586 (366)	0.76 (1.24)	0.000
	June 7	2.2	1822 (239)	0.00 (0.49)	0.000
	June 14	2.3	1151 (143)	1.48 (0.38)	0.133
	June 21	2.4	1086 (92)	1.19 (0.17)	0.339
	June 28	3.2	809 (76)	1.25 (0.13)	0.523
	June30	3.3	732 (68)	1.45 (0.13)	0.590
	July5	4.2	478 (60)	2.00 (0.18)	0.629
	July 13	5.1	688 (147)	1.60 (0.34)	0.185
2006	June 13	2.1 – 2.2	570.2 (72)	3.00 (0.52)	0.250
	June 16	2.3	599 (51)	2.66 (0.32)	0.406
	June 19	2.4	698 (50)	1.65 (0.20)	0.410
	June 23	3.2	678 (40)	1.17 (0.12)	0.525
	June 26	3.3	657 (41)	1.11 (0.11)	0.529
	July 6	4.2	239 (44)	2.39 (0.27)	0.499
	July 10	4.3	256 (68)	2.38 (0.42)	0.289

Data analyzed using SigmaPlot 10 (Systat Software Inc.)

$^z R^2$ is adjusted for the number of independent variables which reflects the degrees of freedom

Similar trends as observed at Brandon occurred at Indian Head in both years of the study, although the relation between grain yield and NDVI was generally stronger in 2005 than it was in 2006 (Table 3.6). Again, the relationship between NDVI and grain yield started out very weak and improved as the growing season progressed. In both 2005 and 2006 at Indian Head, the relationship peaked when the crop was between growth stages 3.3 and 4.1. For the July 7 sensing date in 2005, the crop was in full bloom and the correlation between NDVI and yield was very weak. It has been suggested that the highly reflective flowers of canola and the dropping of leaves after flowering interfere with the ability of NDVI to detect differences in canola growth (Basnyat et al. 2004). However, the relationship between NDVI and grain yield on August 2, 2006 when the crop was in the pod filling stage, was very strong (R^2=0.820). The observed variability in

NDVI at this point in the growing season was probably a result of the higher yielding plots retaining more green leaves and being somewhat behind in maturity.

Table 3.6 Parameter estimates and adjusted^z coefficients of determination for NDVI (x) – yield (y) relationship at various crop stages (Harper and Berkenkamp 1975) for canola plots at Indian Head, SK. Values enclosed in brackets are the standard error of the parameter estimates (n = 96).

			Parameter estimates $y = a*\exp(b*x)$		
Year	Date	Crop Stage	a	b	Adj. R^2
2005	June 5	1 – 2.1	2336 (138)	1.10 (0.60)	0.024
	June 11	2.2 – 2.3	2145 (116)	1.40 (0.37)	0.120
	June 19	2.4 – 2.6	1891 (90)	0.72 (0.10)	0.373
	June 23	3.1 – 3.2	1604 (85)	0.86 (0.09)	0.530
	June 28	3.3 – 4.1	1062 (70)	1.22 (0.09)	0.730
	July 7	4.3 – 4.4	1607 (220)	0.91 (0.26)	0.113
2006	June 1	1 – 2.1	1026 (414)	5.56 (3.14)	0.021
	June 8	2.2 – 2.3	1543 (190)	2.18 (0.82)	0.060
	June 13	2.3 – 2.4	1662 (165)	0.99 (0.38)	0.056
	June 16	2.4 – 2.5	1545 (140)	0.84 (0.23)	0.119
	June 22	2.6 – 3.1	1161 (122)	1.01 (0.17)	0.283
	June 25	3.1 – 3.2	930 (106)	1.29 (0.17)	0.392
	June 28	3.3 – 4.1	638 (79)	1.68 (0.17)	0.554
	August 2	5.3	175 (24)	3.77 (0.20)	0.820

Data analyzed using SigmaPlot 10 (Systat Software Inc.)

$^zR^2$ is adjusted for the number of independent variables which reflects the degrees of freedom

Compared with the previous two sites, the correlation between grain yield and NDVI was weak at Ottawa in 2005 (Table 3.7). However, the results showed the same overall trend whereby the correlation increased in strength as the crop progressed through the vegetative stages, peaked just prior to flowering and became relatively weak during flowering. Unlike at Indian Head, the relationship between grain yield and NDVI was very weak during the pod filling stage and visual inspection of the data suggested that NDVI was saturated with the vast majority of observed NDVI values being between 0.7 and 0.8 (Figures D-33 to D-35). By contrast, the relationship between NDVI and seed yield was strong throughout the vegetative growth stages in 2006 at Ottawa and the strongest relationship occurred just prior to bolting, which was slightly earlier than the previous site-years. A possible explanation for the early development of the relationship between grain yield and NDVI at Ottawa in 2006 may have been the strong positive yield response to increasing seed rates, which was likely evident in the NDVI measurements earlier in the growing season than relative differences in N availability.

Table 3.7 Parameter estimates and adjusted^z coefficients of determination for NDVI (x) – yield (y) relationship at various crop stages (Harper and Berkenkamp 1975) for canola plots at Ottawa, ON. Values enclosed in brackets are the standard error of the parameter estimates (n = 95 in 2005 and n = 72 in 2006).

			Parameter estimates $y = a*\exp(b*x)$		
Year	Date	Crop Stage	a	b	Adj. R^2
2005	June 1	2.1	2762 (185)	0.79 (0.22)	0.111
	June 3	2.1 – 2.2	2746 (181)	0.52 (0.13)	0.127
	June 7	2.4 – 2.5	2648 (178)	0.51 (0.12)	0.161
	June 10	2.5 – 2.7	2236 (215)	0.67 (0.14)	0.196
	June 20	4.2	296 (191)	3.15 (0.84)	0.132
	June 23	4.3	665 (321)	2.17 (0.66)	0.096
	June 29	5.2	723 (360)	2.19 (0.68)	0.095
2006	May 29	2.2	686 (100)	8.86 (1.06)	0.476
	June 2	2.3	1406 (79)	2.11 (0.23)	0.529
	June 5	2.4	1544 (73)	1.29 (0.15)	0.507
	June 9	2.5	1116 (82)	1.14 (11)	0.603
	June 12	2.6	1195 (84)	1.00 (0.10)	0.580
	June 16	2.7	963 (78)	1.32 (0.12)	0.643
	June 19	3.1 – 3.2	441 (85)	2.19 (0.25)	0.539
	June 23	3.3 – 4.1	290 (81)	2.67 (0.35)	0.476
	June 30	4.2 – 4.3	2254 (645)	0.00 (0.41)	0.000
	July 6	4.4 – 5.1	710 (199)	1.92 (0.45)	0.187
	July 21	5.2 – 5.3	730 (362)	1.53 (0.67)	0.058

Data analyzed using SigmaPlot 10 (Systat Software Inc.)

$^zR^2$ is adjusted for the number of independent variables which reflects the degrees of freedom

There was essentially no correlation between NDVI and grain yield until the crop developed 4 – 5 true leaves in either year at Scott (Table 3.8). In both years, the correlation reached peak strength during the bolting stage and, in 2006, became weak when the crop approached full bloom. The overall relationship between NDVI and grain yield was very weak at Scott in 2006 relative to 2005, probably because the hot, dry conditions experienced in 2006 while the crop was flowering reduced the overall potential grain yield (Angadi et al. 2000; Morrison and Stewart 2002; Askouh-Harradj et al. 2006). Raun et al. (2001) explain that strong correlations between grain and NDVI cannot always be reasonably expected because factors such as drought, frost, hail, or disease, can reduce YP after the NDVI data has been acquired.

Table 3.8 Parameter estimates and adjusted^z coefficients of determination for NDVI (x) – yield (y) relationship at various crop stages (Harper and Berkenkamp 1975) for canola plots at Scott, SK. Values enclosed in brackets are the standard error of the parameter estimates (n = 96).

			Parameter estimates $y = a*\exp(b*x)$		
Year	Date	Crop Stage	a	b	Adj. R^2
2005	June 8	2.1 – 2.2	1864 (281)	0.00 (0.39)	0.000
	June 16	2.3	1523 (247)	0.34 (0.27)	0.006
	June 21	2.4	647 (123)	1.39 (0.25)	0.269
	June 24	2.5 – 2.6	384 (83)	1.99 (0.26)	0.426
	June 27	3.1	134 (44)	3.13 (0.38)	0.465
	June 30	3.3	123 (43)	3.32 (0.41)	0.456
2006	June 7	2.2	929 (167)	0.81 (0.97)	0.000
	June 14	2.4	841 (82)	0.94 (0.35)	0.060
	June 16	2.4 – 2.5	814 (63)	0.79 (0.20)	0.126
	June 19	2.5	827 (55)	0.67 (0.15)	0.157
	June 22	2.5	802 (54)	0.59 (0.12)	0.189
	June 26	2.6 – 3.2	684 (68)	0.71 (0.15)	0.195
	June 30	3.3 – 4.1	390 (75)	1.41 (0.26)	0.247
	July 4	4.3	771 (145)	0.50 (0.28)	0.025
	July 6	4.3 – 4.4	1079 (154)	0.00 (0.25)	0.000

Data analyzed using SigmaPlot 10 (Systat Software Inc.)

$^zR^2$ is adjusted for the number of independent variables which reflects the degrees of freedom

At Swift Current in 2005, there was essentially no relationship between NDVI and grain yield before the canola had reached the early bolting stage (Table 3.9). The correlation then improved rapidly as the crop approached flowering, peaked with an R^2 of 0.707 at the start of flowering, and proceeded to weaken as the crop went into full bloom. Although the relationship between NDVI and yield in 2006 at Swift Current was generally slightly weaker than in 2005, the overall trends were the same and the R^2 still peaked at 0.676.

Table 3.9 Parameter estimates and adjusted^z coefficients of determination for NDVI (x) – yield (y) relationship at various crop stages (Harper and Berkenkamp 1975) for canola at Swift Current. Values enclosed in brackets are the standard error of the parameter estimates (n = 96).

			Parameter estimates $y = a*\exp(b*x)$		
Year	Date	Crop Stage	*a*	*b*	Adj. R^2
2005	June 10	2.1	1204 (321)	0.25 (1.50)	0.00
	June 14	2.2	1068 (172)	0.76 (0.70)	0.002
	June 16	2.2 – 2.3	1004 (126)	1.01 (0.50)	0.031
	June 20	2.4 – 2.5	957 (116)	1.04 0.40)	0.056
	June 22	2.5 – 3.1	836 (101)	1.26 (0.32)	0.133
	June 27	3.2 – 4.1	562 (73)	1.75 (0.24)	0.372
	July 4	4.1 – 4.2	218 (34)	3.09 (0.25)	0.707
	July 6	4.2 – 4.3	486 (68)	1.79 (0.23)	0.460
	July 12	4.3 – 4.4	540 (88)	1.94 (0.33)	0.308
	July 18	5.1 – 5.2	638 (147)	1.43 (0.46)	0.097
2006	June 6	1 – 2.1	89 (40)	12.9 (3.3)	0.131
	June 12	2.1 – 2.2	164 (46)	4.49 (1.10)	0.133
	June 15	2.3 – 2.4	223 (30)	3.82 (0.56)	0.304
	June 19	2.3 – 2.5	253 (24)	2.85 (0.33)	0.409
	June 21	2.4 – 2.5	243 (23)	2.82 (0.30)	0.469
	June 23	2.5 – 2.6	232 (22)	1.97 (0.20)	0.516
	June 30	3.3 – 4.1	138 (16)	2.49 (0.20)	0.676
	July 4	4.2 – 4.4	115 (22)	2.48 (0.30)	0.469

Data analyzed using SigmaPlot 10 (Systat Software Inc.)

$^zR^2$ is adjusted for the number of independent variables which reflects the degrees of freedom

The general pattern observed over the course of the growing season was for NDVI to increase through the vegetative growth stages, peak at the early reproductive stages, and decline after flowering, which is similar to the trends for corn reported by Martin et al. (2007). The relatively weak relationship early in the season was likely attributable to the fact that potential yields of crops become increasingly established as the growing season progresses and that the effects of plant populations on NDVI were likely more profound early on (Warren and Metternicht 2005). As canola plants develop, they compensate for low plant populations through increased branching and overall vegetative growth, especially when water and nutrients are in adequate supply (Rood and Major 1984; Angadi et al. 2003). The decline in NDVI and weakening relationship with grain yield observed late in the growing season was likely attributable to the brightly coloured flowers of canola and to the dropping of leaves and overall senescence of the plants (Basnyat et al 2005; Martin et al. 2007). Considering the results observed for all of the site-years, it is clear that the strength of the relationship between NDVI and canola seed yield depends upon the growth stage of the crop at the time of sensing. The relationship between NDVI and grain yield was weak when the canola had four leaves or fewer. From this point onwards, the correlation improved as the growing season progressed and reached peak strength at some point between mid-bolting and the onset of flowering (growth stages 3.2 – 4.1). Once the canola was in full bloom, the correlation between grain yield and NDVI deteriorated rapidly. While the data from Indian Head in 2006 showed a very strong correlation between NDVI and grain yield at the mid-late pod filling stage, this was not the case at Ottawa, thus the strength of the relationship between NDVI and yield during pod filling is uncertain.

3.4.5 Normalizing NDVI to Improve the Relationship with Canola Yield

The next step towards developing empirical equations for estimating canola YP using in-season NDVI measurements was to combine data from the appropriate growth stages from all of the site-years. As previously discussed, we anticipated the necessity to standardize the NDVI measurements collected within a specified ranged of growth stages to account for normal crop growth and development during this period as well as differences between site-years (Raun et al. 2001; Raun et al. 2002). We used the same general methods to estimate YP as Raun et al. (2002), whereby each NDVI measurement was divided by the normalizing value under evaluation. Based on the results presented in Tables 3.5 through 3.9, we compiled all data collected when the canola was between growth stages 2.5 and 4.1 – 4.2, except for that collected at Scott in 2005, for further analysis. We omitted the data from Scott in 2005 from the following analysis because sever hail damage occurred after sensing at this site-year and preliminary analysis showed that the data clearly did not fit with that of the other site-years (data not shown).

When the selected NDVI measurements were plotted against canola seed yield prior to dividing the NDVI values by any of the potential normalizing units, the best-fit exponential curves had an R^2 of 0.340 (Table 3.10). Close visual inspection of the data revealed that the relationship between the NDVI and yield data from Swift Current and Scott in 2006 was somewhat different from the plotted data from the other site-years. The observed grain yields appeared to be relatively low for the corresponding NDVI values from the same plots (Figure E-1).

Dividing NDVI by the number of days between planting and sensing improved the relationship with grain yield from R^2=0.340 to R^2=0.364. While doing so appeared to decrease the variability among the majority of observations, it increased the apparent separation between the data from Swift Current and Scott in 2006 from that of the other site-years (Figure E-2). As previously discussed, it is probable that the hot, dry conditions experienced late in the season at these sites in 2006, in addition to the minor hail damage at Scott 2006, reduced YP after we had collected the NDVI data. Compared with days from planting, dividing NDVI by GDD_0, GDD_5, and CHU resulted in the relationship with canola seed yield becoming subsequently weaker (Table 3.10; Figures

E-2 through E-5). Compared with NDVI on its own (Figure E-1), it appeared that going from GDD_0 to GDD_5 to CHU as normalizing units increasingly widened the gap between the data collected at Scott and Swift Current in 2006 from the remaining site-years (Figures E-3 through E-5). We observed the strongest relationship with grain yield when we divided NDVI by P-Days and doing so considerably increased the correlation compared with NDVI on its own. Apparently, the relatively low optimum and maximum temperatures assumed in P-days better accounted for the decreased growth late in the season at Swift Current and Scott in 2006.

Table 3.10. Parameter estimates and adjusted[z] coefficients of determination describing the exponential relationship between NDVI values divided by days from planting and various heat units (x) and canola seed yield (y) for canola between crop stages 2.5 and 4.2 (Harper and Berkenkamp 1975) at all site-years excluding Scott in 2005. Values enclosed in brackets are the standard error of the parameter estimates (n = 2376).

	Parameter estimates $y = a*\exp(b*x)$		
x-axis	*a*	*b*	Adj. R^2
NDVI[y]	664.9 (21.9)	1.594 (0.049)	0.340
NDVI/DFP	709.0 (20.2)	57.26 (1.597)	0.364
NDVI/GDD_0	698.0 (20.7)	861.8 (24.8)	0.358
NDVI/GDD_5	733.3 (21.7)	536.9 (16.3)	0.335
NDVI/CHU	740.2 (21.8)	856.7 (26.2)	0.331
NDVI/P-Days	656.3 (18.0)	419.0 (10.3)	0.423

Data analyzed using SigmaPlot 10 (Systat Software Inc.)

[z] R^2 is adjusted for the number of independent variables which reflects the degrees of freedom

[y] NDVI – normalized difference vegetation index; DFP – days from planting; GDD_0 – growing degree days (base temperature 0˚C); GDD_5 – growing degree days (base temperature 5˚C); CHU – corn heat units; P-Days – Physiological days

Raun et al. (2005) recommend that data collected from site-years where conditions following sensing have had a definite negative impact on seed yield should generally not be included in empirical datasets for estimating YP with NDVI. In previous work, Raun et al. (2001) demonstrated how including such site-years can weaken the relationship between normalized NDVI measurements and grain yield. Because of the hot, dry conditions in 2006 at Scott and Swift Current and the apparently different relationship between NDVI and yield at these two sites compared with the others, we decided to remove them to see if we could improve the correlations (Table 3.11).

Table 3.11. Parameter estimates and adjusted[z] coefficients of determination describing the exponential relationship between NDVI values divided by days from planting and various heat units (x) and canola seed yield (y) for canola between crop stages 2.5 and 4.2 (Harper and Berkenkamp 1975) at all site-years excluding Scott in 2005 and 2006 and Swift Current in 2006. Values enclosed in brackets are the standard error of the parameter estimates (n = 1799).

	Parameter estimates $y = a*\exp(b*x)$		
x-axis	*a*	*b*	Adj. R^2
NDVI[y]	806.6 (23.0)	1.48 (0.04)	0.444
NDVI/DFP	883.3 (21.1)	51.5 (1.3)	0.474
NDVI/GDD_0	787.4 (18.7)	878.6 (19.7)	0.545
NDVI/GDD_5	782.6 (18.4)	585.3 (12.9)	0.552
NDVI/CHU	780.1 (18.0)	949.6 (20.5)	0.562
NDVI/P-Days	832.8 (19.2)	370.1 (8.6)	0.528

Data analyzed using SigmaPlot 10 (Systat Software Inc.)

[z] R^2 is adjusted for the number of independent variables which reflects the degrees of freedom

[y] NDVI – normalized difference vegetation index; DFP – days from planting; GDD_0 – growing degree days (base temperature 0°C); GDD_5 – growing degree days (base temperature 5°C); CHU – corn heat units; P-Days – Physiological days

Compared with the previously discussed analysis, removing the data from Scott and Swift Current in 2006 from the combined analysis substantially improved the correlation between NDVI and grain yield, with the R^2 increasing from 0.340 to 0.444 (Tables 3.10 and 3.11). Furthermore, in this analysis, the relative performance of the divisors differed from when Scott and Swift Current 2006 were included. Again, dividing NDVI by DFP improved the correlation between NDVI and grain yield, increasing the R^2 from 0.444 to 0.474 (Table 3.11). However, unlike the first analysis, dividing NDVI by GDD_0 was a substantial improvement over DFP and using GDD_5 and CHU to standardize NDVI resulted in successively increasing R^2 values. Furthermore, the correlation between NDVI divided by P-Days and grain was weaker than for NDVI divided by the other heat units, though not DFP. For all practical applications, GDD_0,

GDD_5, and CHU were equally well suited for standardizing NDVI, as the observed R^2 values for each of these were similar.

3.5 CONCLUSIONS

Overall, the combination of locations, years, N fertilizer rates and seeding rates used in this study resulted in a very wide range of NDVI values and grain yields being realized. The grain yields of the individual plots included in the final analysis ranged from less than 200 kg ha^{-1} to more than 5000 kg ha^{-1} and the NDVI values ranged from less than 0.20 to, in rare instances, greater than 0.90. The observed range of both NDVI values and grain yields provided a diverse data set for developing empirical equations to estimate the potential yield of canola from in-season NDVI measurements. Furthermore, the plant populations were highly variable both from one site-year to the next and within individual site-years, thus any models derived from this data should account for variability in crop establishment.

When all of the NDVI data collected between growth stages 2.4 and 4.2 (Harper and Berkenkamp 1975) were combined with the exception of Scott in 2005 and plotted against grain yield, there was a reasonably strong exponential correlation even when NDVI was not normalized (R^2=0.340). However, when the data from Scott and Swift Current were removed from the combined analysis, the correlation between NDVI and grain yield was improved substantially (R^2=0.444). The best correlation with grain yield in the final analysis occurred when NDVI was divided by CHU (R^2=0.562), but P-Days gave the best results when data from Swift Current and Scott in 2006 were included (R^2=0.423). That P-days performed best in the first combined analysis suggests that P-Days, with an optimal temperature of 17° C and a maximum temperature of 30° C, better accounted for the lack of growth during extremely hot periods than the other units did. When we removed the affected site-years under the justification that post-sensing environmental conditions at these sites were such that they had a substantial negative affect on grain yield, however, P-Days did not perform as well as the other heat units, although it was still an improvement over DFP.

Because of the complexity of calculating P-Days and their inconsistent performance relative to the other heat units, we probably would not recommend P-Days as the choice unit for normalizing NDVI. The remaining three heat units performed similarly in both of the combined analyses and GDD_0, GDD_5, and CHU were all well suited for normalizing NDVI to estimate canola YP. While DFP did not perform as well any of the heat units in the final combined analyses, it was still a substantial improvement over NDVI on its own. As such, in situations where temperature data are not available, dividing NDVI by the number of days between planting and sensing is a viable option.

3.6 ACKNOWLEDGEMENTS

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4.0 FINE-TUNING NITROGEN FERTILIZER RATES IN CANOLA USING SENSOR-BASED ESTIMATES OF YIELD POTENTIAL AND RESPONSIVENESS TO NITROGEN

4.1 ABSTRACT

The challenge is choosing nitrogen (N) fertilizer rates that are appropriate for crop, soil, and growing conditions. Field experiments were completed to evaluate the potential of optical sensors and in-crop N applications to better match N fertilizer rates with canola requirements. The treatments were N management strategies that included: 1) Farmer Practice (FP), where a full rate of N fertilizer was applied at seeding, 2) N-Rich (NR), where an elevated rate of N was applied at seeding, 3) Split-Fixed (SF), where a rate of N equivalent to that applied in the FP treatment was split between seeding and an in-crop application, 4) a variable rate application (VRA) where a reduced rate of N was applied at seeding and variable rates, determined using optical sensors, were applied in-crop, and 5) Reduced N (RN), where a reduced rate of N was applied at seeding. An check that did not receive any fertilizer N was also included. We measured the effects of the strategies on grain yield, grain N content, grain N removal, fall residual soil NO_3-N, and agronomic N use-efficiency of canola. Grain yields of the VRA treatments were not different from the FP treatment in three of four cases, despite having received 20 – 56 kg ha^{-1} less fertilizer N in total. At the site-year where a difference was observed, there was no response to post-emergent N due to extremely dry conditions late in the growing season and the FP treatment yielded higher than any of the treatments where split applications of N were applied. Agronomic N use-efficiency was affected at two site-years, whereby efficiency was lowest in the NR treatment and highest in the VRA and RN treatments. Overall, while sensor-based N management is technically

feasible and typically results in reduced fertilizer N use, post-emergent N applications in dryland agriculture are not without risk and the potential economic gains associated with adopting this technology remain uncertain.

4.2 INTRODUCTION

The major factors to consider for nitrogen (N) fertilizer management in crop production are the form, placement, timing, and rate of N. The major sources of fertilizer applied in western Canada are urea and anhydrous NH_3 and, to a lesser extent, urea ammonium nitrate (UAN) and monoammonium phosphate (Korol 2002). While they must be treated differently in certain respects, the various forms of N fertilizer perform similarly if managed appropriately (Johnston et al. 1997; Grant et al. 2002). In terms of fertilizer placement, banding is the preferred method among producers in western Canada and is generally more effective than broadcast applications, especially under no-till conditions (Harapiak et al. 1993; Grant et al. 2002). Regarding timing, applying N as close as possible to the time when the crop will utilize it minimizes the length of the period over which N can be lost. According to Malhi et al. (2007), the maximum rate of N uptake in canola occurs around the late bud-forming stage (28 – 35 days after emergence) while total N uptake peaks between flowering and early ripening (63 – 75 days after emergence).

While it is ideal to apply N fertilizer as close to the time of plant uptake as possible, practical considerations such as fertilizer prices, conflicts with other operations and equipment configuration often prevail in practice. Banding anhydrous NH_3 or urea in the fall or early spring is a common and generally effective practice (Grant et al. 2002; Tiessen et al. 2005); however, modern seeding equipment allows producers to safely apply the canola crop's entire fertilizer requirements at the time of seeding (Johnston et al. 2002). Single-pass seeding combined with no-till management minimizes soil disturbance which has advantages such as increasing soil organic matter (Malhi et al. 2006) along with grain yields and water use efficiency compared with conventional tillage systems (Lafond et al. 2006). Consequently, it is probable that the efficiency of banded N fertilizer is higher in the temperate Canadian Prairies than the estimated world-wide NUE estimate of 33% (Raun and Johnston 1999). In north-central Alberta, Malhi and Nyborg (1991) recovered 32 – 50% of the ^{15}N-labelled urea banded at seeding in the mature plants (grain plus straw) and 66 – 74% when soil N was accounted for. However, because residual soil mineral N is vulnerable to leaching (Campbell et al. 1984) and denitrification (Lemke et al. 1998) prior to crop uptake, it is best to maximize the ratio of fertilizer N recovered in grain and crop residues to that recovered in the soil (Malhi and Nyborg 1991). A potential method of achieving this and increasing NUE beyond the levels currently achieved in western Canada is to improve our ability to match the rates and timing of N fertilizer applications with crop requirements more consistently.

Choosing the correct N rate to apply is not a trivial task. The quantity of N that crops require is a function of yield potential (YP) as well as the soil's ability to supply N. Plant available soil N includes both residual N at planting and N mineralized from soil organic matter during the growing season. It is very difficult, however, to estimate both the YP of a specific crop and the soil's ability to supply N at the time when most fertilizer N is applied. Consequently, our ability to accurately determine the optimum rate of N fertilizer to apply on a field specific basis in any given year is limited.

For lack of a better alternative, producers often use yield goals when determining N fertilizer rates. As a method of setting realistic yield goals, Johnston and Dowbenko (2006) recommend looking at the production of a given crop in a field for the past seven to ten years, removing any low yields resulting from drought or bad management, and averaging the yields from the remaining years. Yield goals should be flexible and allow for adjustments of 10 – 20% either way depending on current economic considerations (Johnston and Dowbenko 2006) and/or spring soil moisture conditions (Andreiuk 2004). Depending on the yield goal that a producer chooses, the recommended N fertilizer rates can vary extensively (Table 2.4) and, because of variability in both grain yields and the quantity of N that the soil can supply, yield goals on their own are typically weak indicators of the optimal N rate for a field (Scharf 2001).

Discounting residual soil NO_3-N from crop N requirements can improve fertilizer N recommendations based on yield goals. The preplant soil test involves collecting a large number of samples for a given field, avoiding any non-representative areas such as headlands, previous fencelines, or yard sites, and submitting a single, composite soil sample from each field for analysis. While traditional, composite soil tests can be useful tools for improving fertilizer recommendations compared with no soil test, they also have important limitations. Most commercial laboratories measure only the amount of NO_3-N in the soil sample, which provides no indication of how much N may be mineralized from soil organic matter over the course of the growing season. While organic N fractions such as the Illinois Soil Test N (Khan et al. 2001) and hydrolyzed hot KCl-N (Jalil et al. 1996) have been proposed to estimate mineralizable N, they too are unable to account for factors such as soil temperature and moisture (Akinremi et al. 1999) and soil wetting and drying cycles (Mikha et al. 2005). Another drawback of traditional, composite soil tests is that they do not account for spatial variability in residual N concentrations, which can be high (Raun et al. 1998). While intensive sampling procedures, such as grid or landscape directed sampling, allow spatial variability in soil N fertility concentrations to be characterized (Franzen et al. 1998), the labour requirements and costs of such procedures limit their utility in production agriculture. At best, traditional, composite soil tests provide a good starting point for determining the N requirements of crops, but their limitations prevent them from being wholly reliable indicators of optimal N rates.

Recent developments in optical sensing technology have the potential to improve our ability to estimate both the YP of crops and their potential responsiveness to additional N inputs as a means of fine-tuning N fertilizer recommendations (Raun et al. 2002). The GreenSeeker^{TM} sensor (NTech Industries) and the Crop Circle^{TM} (Holland Scientific) are two ground-based sensors that actively emit near infrared (NIR) and visible bandwidths of light and measure the amount of emitted light reflected off of the crop canopy. The GreenSeeker^{TM} (red/NIR) emits and measures light at 671±6 nm and 780±6 nm while the Crop Circle^{TM} (red/NIR) uses light at 650 and 890 nm. A unique feature of the GreenSeeker^{TM} sensors is their ability to integrate with application equipment and direct variable rate applications.

Normalized difference vegetation index (NDVI), originally proposed by Rouse et al. (1974), is one of the most widely used vegetation indexes calculated with optical sensors. Normalized difference vegetation index is sensitive to subtle changes in vegetated surfaces and is an indirect measure of aboveground biomass and N uptake (Moges et al. 2004; Freeman et al. 2007). The NDVI of a crop and its grain yield are also well correlated with one another and, when standardized to account for normal crop development, can be used to estimate a crop's YP partway through the growing season (Raun et al. 2001; Raun et al. 2002). Raun et al. (2001) showed that the sum of two post-dormancy NDVI measurements divided by the number of growing degree-days (GDD) accumulated between the two measurements was well correlated with grain yield. These methods were later refined so that YP was estimated using a single NDVI measurement divided by the number of days between planting and sensing where GDD was greater than zero (Raun et al. 2002). Empirical equations based on previously collected data are required to convert the standardized NDVI measurements to grain YP (Raun et al. 2001). Sensor-based estimates of YP could provide an objective method of estimating YP, an important factor for estimating post-emergent (PE) N requirements.

Establishing high N reference areas in fields where N will not be limiting to grain yields at seeding makes it possible to use optical sensors to estimate the potential for obtaining a response to PE N applications (Raun et al. 2002). While such methods of N management have not previously been documented for canola, Behrens et al. (2004) showed that the NDVI of fertilized canola canopies at growth stages, 3.1 and 4.1 (Harper and Berkenkamp 1975) were consistently higher than for unfertilized canola canopies. This is evidence that optical sensors may be capable of detecting relative differences in N status of canola which, when considered along with the YP estimates, facilitates estimating PE N requirements (Raun et al. 2002). Because NDVI is a crop-based indicator of N status, it simultaneously accounts for both the soil's capacity to supply N and any factors other than N availability that may be limiting YP at the time of sensing (Ma et al. 2005).

Implementing sensor-based N management strategies requires that a yield response to PE N applications can still be attained at the time the sensors are being used. Furthermore, when applying N fertilizer to established crops, producers are limited to either low disturbance in-soil applications using specialized equipment or surface applications of fertilizer N. While there are advantages to placing PE N beneath the soil surface, it has been established that these advantages are not usually sufficient to justify the added cost of the field operation required to do so (Holzapfel et al. 2007a). While it is possible to postpone the entire quantity of fertilizer N in canola up to 30 days after seeding without reducing grain yield, doing so can result in severe yield penalties in years where surface applications of UAN to wet soils are followed by drought (Holzapfel et al. 2007a). However, as long as 50 – 66% of crop N requirements are supplied up front, the remainder can be postponed to the bolting stage with no losses in grain yield and applying some N at the time of seeding decreases the risks associated with PE N applications (Lafond et al. 2007).

The objective of this study was to evaluate several different N management strategies for canola production, with the prime objective of evaluating the sensor-based methods against the benchmark practice of applying the entire quantity of fertilizer N at seeding. The major factors of interest were grain yield, grain N content, the quantity of N removed in the seed, and agronomic nitrogen use efficiency (ANUE). Despite this crop's relatively high N requirements and economic importance in western Canada, to the best of our knowledge, this approach to N management has not yet been evaluated for canola.

4.3 MATERIALS AND METHODS

4.3.1 Site Descriptions

Field experiments were conducted at Agriculture and Agri-Food Canada locations at Indian Head and Scott, SK. The soil at Indian Head is an Indian Head heavy clay (Rego Black Chernozem) and the soil at Scott is an Elstow loam (Orthic Dark Brown Chernozem). Indian Head is located in the thin Black Soil Zone in the southeast part of Saskatchewan (53˚ 33.0' N, 103˚ 39.0 W) and receives an average of 335 mm of precipitation annually. Scott is located northwest of Saskatoon (52˚ 21.6' N, 108˚49.8 W) in the Dark Brown soil zone and, on average, receives 269 mm of precipitation each year. The mean yearly temperatures at Indian Head and Scott are 2.6˚C and 1.6 ˚C respectively. The two sites, with their different soil types and moisture regimes, broadened the range of conditions under which we could evaluate sensor-based N management strategies.

4.3.2 Treatment Descriptions and Experimental Design

The field experiments at all four site-years included the following five treatments: 1) an unfertilized check where no fertilizer N was applied, 2) N-Rich (NR), where all fertilizer N was applied as urea at the time of seeding at rates considered sufficient to ensure that N would not become limiting, 3) Farmer Practice (FP), where all fertilizer N was applied as urea at the time of seeding at rates considered sufficient to support average yields 4) Split application / Fixed rate (SF), where a reduced rate of N was applied as urea at the time of seeding and urea-ammonium nitrate (UAN) was surface dribble-banded in-crop to bring the total fertilizer N rate up to that of the FP treatment and 5) Variable Rate Application (VRA), where the same rate of urea was applied at seeding as for the SF treatment and a variable rate of UAN was applied in-crop with the rates determined using a sensor-based N application algorithm. In both years at Indian Head, we included a Reduced N (RN) treatment where an equivalent rate of urea at seeding was applied as in the previous two treatments and no further N was applied.

The N application algorithms were based on empirical YP curves that were developed using all of the data available to us at the time for each of the two years. To generate the curves, we used the same methods as described in Chapter 3 and divided NDVI by the GDD (base temperature 0˚ C) accumulated between seeding and sensing. The actual empirical data and scatter plots used to derive the YP equations in both years appear in Appendix F. In the N application algorithm used in 2005, the actual best-fit curve was adjusted upwards by 33% under the assumption that the YP estimated during the growing season is often higher than the actual yields realized at harvest (William R. Raun, personal communication). In 2006, we tested two variations of the N application algorithm using two separate versions of the empirical equation to estimate canola yield potential. In the variation of the algorithm hereafter referred to as VRA1, we used the actual best-fit YP curve without adjusting the curve upwards. In the treatment hereafter referred to as VRA2 we estimated YP using the adjusted curve. In 2005, we calculated the equations using Excel 2000 (Microsoft Corporation) and in 2006, we used SigmaPlot 2000 (Systat Software, Inc.). The three equations used over the course of the study are presented relative to one another in Figure 4-1.

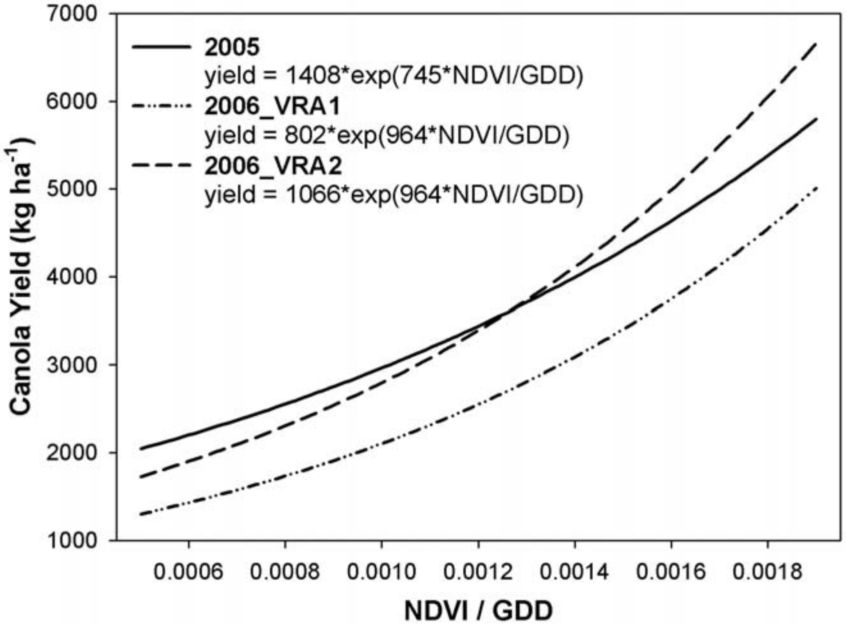

Figure 4-1. Variations of the exponential equations used to estimate canola yield potential in the variable rate treatments for the 2005 and 2006 growing seasons.

Calculating PE N rates in the variable rate treatment was a multiple step process. Prior to each PE N application, we determined the number of GDD that had accumulated from the day after seeding to the day prior to sensing inclusive, and measured the NDVI of each plot using handheld GreenSeeker™ sensors. At Indian Head in 2005 and Scott in 2005 and 2006, we used the average NDVI of the N rich plots to estimate the upper canola YP for the corresponding site-year. At Indian Head in 2006, we estimated the upper YP separately for each replicate using the NDVI of the NR plot within the same replicate. We divided the NDVI values by GDD and used the resultant value in the appropriate exponential equation to estimate YP. Using the estimated difference between the YP of the VRA and NR plots, we calculated the required N rates for each VRA plot separately using Equation 4.1. The N concentration of canola seed was assumed to be 33 g N kg seed^{-1} at all site-years.

$$N_{Req} = GN_{NRICH} - GN_{VRA} / 0.5 \qquad [4.1]$$

where N_{Req} is the estimated quantity of fertilizer N required and GN_{NRICH} and GN_{VRA} are the estimated amounts of N removed in grain of the NR and the VRA treatment respectively. We divided the difference in grain N by an efficiency factor of 0.5 under the realization that some of the N fertilizer applied may be lost (Rawluk et al 2001; Holzapfel et al. 2007b), temporarily immobilized (Trinsoutrot et al. 2000), or not utilized by the crop. The field experiments were set up as a randomized complete block design with four replicates at all site-years except for Scott in 2006, where certain treatments were represented more than once in some replicates and not at all in others. The data from Scott 2006 was analyzed as a completely randomized design.

4.3.3 Crop Management

The experiments were conducted in fields that had been continuously cropped under no-till management for periods exceeding 10 years. The canola was direct seeded into standing cereal stubble in the oilseed phase of four-year cereal – pulse – cereal – oilseed rotations. We targeted early seeding and the actual seeding dates ranged from May 11 – May 19 (Table 4.1). Seeding was completed using two separate high clearance hoe press drills (one for each site). At Indian Head, the drill was equipped with 10 openers spaced 20 cm apart while at Scott the 10 openers were spaced 25 cm apart. Both drills were equipped with double-offset discs spaced half way between every second opener through which granular urea was applied. Refer to Table 4.1 for selected agronomic information for each site-year.

Fertility of all nutrients other than N were managed the same for all of the treatments, including the unfertilized check, within each site-year. At Indian Head in both years, 40 kg P_2O_5 ha^{-1} was applied as triple super-phosphate (0-45-0-0), with 15 kg

P_2O_5 ha^{-1} seed-placed and the remainder dual-banded with the urea. Potassium sulphate (0-0-50-17) was broadcast prior to seeding both years at Indian Head at 45 kg K_2O ha^{-1} and 15.3 kg S ha^{-1}. At Scott, a granular blend of triple super phosphate, potassium chloride, and ammonium sulphate with a nutrient composition of 4-17-17-7 was seed placed at 84 and 73 kg ha^{-1} in 2005 and 2006 respectively.

Table 4.1. Selected agronomic information for N fertilizer management experiments with canola at Indian Head and Scott in 2005 and 2006.

	Indian Head		Scott	
Field Operation	**2005**	**2006**	**2005**	**2006**
K_2SO_4^{z} application date	April 28	October 26	n/a	n/a
K_2SO_4 application rate	90 kg ha^{-1}	90 kg ha^{-1}	n/a	n/a
Pre-emergent herbicide application (products and rates enclosed in brackets)	May 9 (890 g ha^{-1} glyphosate)	October 19 (05) (1700 g trifluralin) May 16 (440 g glyphosate ha^{-1})	May 15 440 g glyphosate ha^{-1}	May 10 440 g glyphosate ha-^{1}
Seeding date	May 11	May 15	May 19	May 18
Seeding rate	5.3 kg ha^{-1}	5.02 kg ha^{-1}	5.3 kg ha^{-1}	5.3 kg ha^{-1}
In-crop herbicide application (products and rates enclosed in brackets)	June 3 (196 g ^{1} clopyralid ha^{-}); 06/06/05 (500 g glufosinate ammonium ha^{-1} plus 15 g clethodim ha^{-1})	June 23 (500 g glufosinate ammonium ha^{-1} plus 15 g clethodim ha^{-1})	June 16 500 g glufosinate ammonium ha^{-1}	June 13 500 g glufosinate ammonium ha^{-1}
NDVI measurement date	June 23	June 25	June 24	June 28
PE N application date	June 24	June 29	June 27	June 30
Swathing date	August 30	August 10	Straight cut	Straight cut
Harvest date	September 6	August 29	September 30	August 23
Fall soil sampling date	October 21	September 14	October 27	August 30

^{z}Nutrient Analysis of 0-0-50-17

At both sites, the fertilizer N applied at seeding was mid-row banded granular urea. In 2005 at both sites, we adjusted the N rates applied at seeding for residual NO_3-N to target 250, 150, and 90 kg N ha^{-1} in total for the NR, FP, and split/reduced N treatments respectively. In 2006 at Scott 160, 100, and 66 kg ha^{-1} of fertilizer N was applied at seeding in the NR, FP, and split N treatments respectively. At Indian Head in 2006 the N rates at seeding were determined using the same methods as in 2005, but an error at top-dressing resulted in 24 kg ha^{-1} less total fertilizer N being applied in the SF treatment than in the FP treatment. Post-emergent N was applied using tractor-mounted applicators that were 1.8 m wide with six openers spaced 30 cm apart. The applicator was kept approximately 40 cm above the ground and the liquid UAN dribbled onto the soil surface in bands. At the time of topdressing, we drove over all of the plots with the same tractor used to apply PE N to equalize the effects of wheel tracks. A summary of residual N levels prior to seeding and applied N rates for each site-year appears in Table 4.2.

Table 4.2. Residual NO_3-N (kg N ha^{-1}) prior to seeding and applied fertilizer rates (kg N ha^{-1}) for canola at Indian Head and Scott in 2005 and 2006.

Location	Year	Trtmnt	Residual NO_3-N 0 – 60cm	N_{SEED}^{z}	N_{PE}^{y}	N_{TOT}^{x}
			kg N ha^{-1}			
Indian Head	2005	FP^{w}	48	100	0	100
		NR^{w}		200	0	200
		Split^{w}		41	60	101
	2006	FP	43	106	0	106
		NR		191	0	191
		Split		48	34^{v}	82^{v}
Scott	2005	FP	34	116	0	116
		NR		216	0	216
		Split		56	60	116
	2006	FP	40	103	0	103
		NR		163	0	163
		Split		69	34	103

^{z}Quantity of fertilizer N supplied at seeding as mid-row banded granular urea

^{y}Quantity of fertilizer N supplied post-emergent (PE) as surface dribble banded urea ammonium nitrate (UAN)

^{x}Total quantity of fertilizer N applied

^{w}FP – Farmer Practice; NR – Nitrogen rich; Split - all treatments that received split or reduced applications of fertilizer N (SF, VRA, and RN). Nitrogen rates applied post-emergent apply only to the split application / fixed rate (SF) treatment.

^{v}SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

InVigor^{TM} 5020, a Glufosinate-ammonium tolerant (LibertyLink^{TM}), hybrid canola cultivar, was used at all site-years at a targeted rate of 100 viable seeds m^{-2}. Mean plant densities (plants m^{-2}) were determined for each plot when the canola had between two and four leaves by averaging the number of plants in four 1m rows. Competition from weeds was controlled using registered herbicides at the recommended growth stages of crops and weeds and neither foliar fungicide nor insecticide applications were considered necessary over the duration of the study. At Indian Head in 2005, the glyphosate applied prior to emergence did not provide adequate control of Canada thistle so we applied 196 g clopyralid ha^{-1} at the 1 – 2 leaf stage, which was slightly earlier than the recommended growth stage for canola of 2 – 6 leaves. No visual evidence of herbicide damage was observed as a result of this early herbicide application. Other than the clopyralid applied at Indian Head 2005, 500 g glufosinate-ammonium ha^{-1}, with the addition of 15 g clethodim ha^{-1} both years at Indian Head but not at Scott, were the only in-crop herbicides applied.

At Indian Head, the entire plots were swathed when 40 – 60% of the seeds on the main raceme seed had changed colour and harvested when mature using Wintersteiger^{TM} plot combines. The plots at Scott were straight-cut at maturity using Wintersteiger^{TM} plot combines and the actual dates of all harvest operations are presented in Table 4.1. The harvested grain samples were dried to constant moisture content, cleaned and weighed. All grain yields are corrected to a seed moisture content of 10% and reported as kg ha^{-1}. Grain N was determined using the Kjeldahl method at all site-years except for Scott in 2005 where a near infrared protein analyzer was used (Daun et al. 1994). To convert percent protein to percent grain N at Scott in 2005, percent protein was divided by a factor of 6.25 (Williams et al. 1998).

Soil samples were collected from each plot after harvest and analyzed for residual NO_3-N. In 2005, we collected one soil core from each plot and analyzed the zero to 15 cm and 15 – 60 cm profiles separately. In 2006, we combined three separate soil cores from each plot into a composite sample for zero to 60 cm profile only. At Scott, two soil samples from each plot were combined and analyzed for NO_3-N for the zero to 15cm, 15 – 30cm, 30 – 60cm, and 60 – 90cm depths. For simplicity, only results for the 0 – 60cm profiles are presented in this chapter; however, summary tables for each separate profile depth are presented in Appendix G.

Agronomic nitrogen use-efficiency (ANUE) was calculated for each fertilized plot using equation 4.2 (Fageria and Baligar 2003; Fageria and Baligar 2005).

$$\text{ANUE} = (Y_{\text{FERT}} - Y_{\text{CHECK}}) / N_{\text{APPLIED}} \qquad [4.2]$$

where Y_{FERT} is the grain yield (kg ha^{-1}) of the fertilized treatment, Y_{CHECK} is the grain yield (kg ha^{-1}) of the unfertilized check, and N_{APPLIED} is the total quantity of fertilizer N applied (kg ha^{-1}). Agronomic NUE is expressed as kg grain yield kg N applied^{-1}.

4.3.5 Statistical Analyses

Data were analyzed separately for each site-year using the general linear model (GLM) procedure of SAS 9.1 (SAS Institute Inc.). The Ryan-Einot-Gabriel-Welsch multiple range test, which controls the Type I experiment-wise error, was used for mean separations and contrasts were used to compare specific groups of treatments with one another. All treatments were included in the analyses of all response variables with the exception of ANUE where we excluded the unfertilized check. All treatment differences were declared significant at the 5% probability level.

4.4 RESULTS AND DISCUSSION

4.4.1 Growing Season Conditions

Growing season conditions in 2005 and 2006 were very different from one another at both Indian Head and Scott. Early spring moisture conditions were excellent at Indian Head in both years and Scott in 2006. Spring moisture conditions were somewhat drier at Scott in 2005 (Table 4.3). Note that the soil was sampled to a depth of 90 cm at Scott compared with 120 cm at Indian Head.

Table 4.3. Total spring soil moisture content (mm) at Indian Head and Scott in 2005 and 2006.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Soil profile (cm)		spring soil moisture (mm)		
0 – 60^{z}	155	236	111	190
60 – 120 (90^{y})	214	253	36	116
Total	**369**	**489**	**147**	**306**

^{z}Assuming soil bulk density of 1.25 and 1.27 g cm^{-3} for 0 – 60 cm and 60 – 120 cm profiles at Indian Head, respectively and 1.33 and 1.58 g cm^{-3} for the 0 – 60 cm and 60 – 90 cm profiles at Scott respectively
^{y}Soil sampled to a depth of 120 cm at Indian Head and 90 cm at Scott

Temperatures at Indian Head were relatively cool during the 2005 growing season with well below normal monthly temperatures from April to August inclusive (Table 4.4). The overall average temperature for the 2005 growing season at Indian Head was one full degree Celsius lower than the long-term average for the same period. Temperatures in the 2006 growing season at Indian Head were closer to normal, with the overall mean growing season temperature within half a degree of the long-term average and monthly temperatures that were very close to the long-term average from May through August. Temperatures at Scott were close to average in 2005 and well above average in 2006, with the highest temperatures in 2006 occurring in July and August.

Table 4.4. Mean monthly temperatures (ºC) recorded at Scott and Indian Head during the 2005 and 2006 growing seasons along with the thirty-year average temperatures for these sites.

	Indian Head			Scott		
	2005	**2006**	**LT^z**	**2005**	**2006**	**LT^z**
	mean monthly temperature (ºC)					
April	5.5	7.3	4.0	5.8	7.1	3.6
May	8.7	11.2	11.4	9.2	10.9	10.9
June	14.8	16.0	16.1	13.4	15.3	15.2
July	16.9	17.9	18.4	16.2	18.8	17.0
August	15.6	17.3	17.5	13.5	16.8	16.3
Average	**12.3**	**13.9**	**13.5**	**11.6**	**13.8**	**12.6**

^{z}Long term averages according to Environment Canada's Canadian Climate Normals (1971 – 2000)

Despite below normal precipitation levels in April, ample spring soil moisture and normal to above normal precipitation from May to August (Table 4.5) ensured good overall water availability at Indian Head in 2005. In contrast, moisture availability in 2006 at Indian Head started out sufficient, but conditions became very dry late in the season with no significant rainfall events occurring between June 24 and the time the plots were harvested (Appendix C). Scott was relatively wet in 2005, with total growing season precipitation levels that exceeded the long-term average by nearly 100 mm. The plots at Scott in 2005 were damaged by hail while in full bloom, with damage estimates from the surrounding area ranging from 60 – 85%. The damage to the plots was considered to be uniformly distributed across the study area and the warm, wet conditions throughout July and August allowed the canola at Scott 2005 to recover well. Overall precipitation levels in 2006 at Scott were close to normal, though less than half the average precipitation was received in July, which was also considerably warmer than normal. Again in 2006, the plots at Scott were damaged by hail, with yield losses estimated at approximately 30% and considered evenly distributed across the study area.

Table 4.5. Total monthly precipitation levels (mm) recorded at Scott and Indian Head during the 2005 and 2006 growing seasons along with the thirty-year average precipitation levels for these sites.

	Indian Head			Scott		
	2005	**2006**	**LT^z**	**2005**	**2006**	**LT^z**
	precipitation (mm)					
April	6.8	73.2	24.6	27.4	32.0	23.6
May	57.6	39.0	55.7	41.4	62.8	35.9
June	99.2	80.4	78.9	100.0	66.8	62.5
July	59.2	5.6	67.1	76.8	34.6	70.9
August	98.0	11.8	52.7	88.6	47.0	43.1
Total	**321**	**210**	**279**	**334**	**243**	**236**

^{z}Long term averages according to Environment Canada's Canadian Climate Normals (1971 – 2000)

4.4.2 Crop Establishment, NDVI and Variable Rate N Requirements

Crop establishment was considered adequate at all site-years with plant densities ranging from 62 – 130 plants m^{-2} (Table 4.6). The Canola Council of Canada recommends targeting between 75 – 150 plants m^{-2} (Canola Council of Canada 2005), which is somewhat higher than the populations recommended by Angadi et al. (2003), who found that canola yields were largely unaffected by plant populations ranging from 20 – 80 plants m^{-2}. Nitrogen management did not affect canola establishment in any cases; thus, NH_3 toxicity was not considered a confounding factor at the high N rates.

The NDVI of each plot was measured using a handheld GreenSeeker^{TM} sensor one to four days prior to the date of the PE UAN applications, which took place between June 24 and June 30 (Table 4.1). Growth stages of the canola at the time of topdressing ranged from 3.1 – 3.3 (Harper and Berkenkamp 1975). The addition of N fertilizer consistently increased NDVI of the canola canopies, with the NDVI of the unfertilized check always being lower than the fertilized treatments, separately or combined (Table 4.7). Behrens et al. (2004) also observed higher NDVI values for fertilized rapeseed canopies than for unfertilized crops. Normalized difference vegetation index has also proven to be well suited for detecting differences in N uptake for wheat (Moges et al. 2004) and corn (Freeman et al. 2007).

Table 4.6. Plant densities (plants m^{-2}) of canola established under various N management strategies at Indian Head and Scott in the 2005 and 2006 growing seasons.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management	plants m^{-2}			
Check	72	81	113	62
N Rich (NR)	72	75	130	64
Farmer Practice (FP)	84	78	113	62
Reduced N (RN)	77	81	na	na
Split / Fixed (SF)	73	68[y]	128	76
Variable Rate 1 (VRA1)	na	68	na	60
Variable Rate 2 (VRA2)	83	68	111	66
	Analysis of Variance			
Source	p > F			
Treatment	0.572	0.896	0.685	0.525
Replicate	**0.002**	0.920	**0.005**	[w]
Residual C.V. (%)	16.1	27.5	19.4	18.4
	Selected Contrasts			
	p-value			
Check vs Rest	0.399	0.496	0.585	0.596
NR vs RN+SF+VRA	0.464	0.719	0.409	0.618
FP vs RN+SF+VRA	0.385	0.587	0.678	0.453

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc) with the Ryan-Einot-Gabriel-Welsch multiple range test used for means separations.

[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

[x] Contrasts include both VRA treatments in 2006 at both sites

[w] Data from Scott 2006 analyzed as a completely randomized design

na – Treatment not included at this site-year.

The tendency was always for the NDVI of the VRA treatment to be lower than that of the NR treatment, although 2006 at Indian Head was the only site-year where the difference was significant. The NR treatment had the highest mean NDVI at all of the site-years except Scott in 2005, where the FP treatment had the highest mean NDVI. Furthermore, the NR treatment had a significantly higher NDVI than the combined split / reduced N treatments in both years at Indian Head, but neither year at Scott. The NDVI of the FP treatment was higher than that of the reduced N treatments in three out of four site-years, the exception being Scott in 2006. At Scott 2006, the only significant difference in NDVI among the treatments was between the unfertilized check and all other treatments, although the NDVI of the NR treatment tended to be higher than that of the combined split N treatments (p = 0.065).

Table 4.7. NDVI of canola grown under different N management strategies at Indian Head and Scott in 2005 and 2006. Canola was between the early-bolting stage and the start of flowering (GS 3.1 – 4.1) and NDVI was determined using handheld GreenSeeker$^{\text{TM}}$ sensors just prior to applying the PE N fertilizer.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management		NDVI		
Check	0.271b	0.502c	0.463c	0.637b
N Rich (NR)	0.406a	0.769a	0.594ab	0.749a
Farmer Practice (FP)	0.400a	0.751ab	0.637a	0.714a
Reduced N (RN)	0.356a	0.711b	na	na
Split / Fixed (SF)	0.351a	0.730ab[y]	0.562b	0.703a
Variable Rate 1 (VRA1)	na	0.714ab	na	0.714a
Variable Rate 2 (VRA2)	0.382a	0.714ab	0.577b	0.713a
		Analysis of Variance		
Source		p > F		
Treatment	**<0.001**	**<0.001**	**<0.001**	**0.007**
Replicate	**0.012**	0.057	**0.005**	[w]
Residual C.V. (%)	8.4	3.6	4.1	4.9
		Selected Contrasts		
		p-value		
Check vs Rest	**<0.001**	**<0.001**	**<0.001**	**<0.001**
NR vs RN+SF+VRA[x]	**0.028**	**0.002**	0.119	0.065
FP vs RN+SF+VRA	**0.047**	**0.028**	**<0.001**	0.829

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc) with the Ryan-Einot-Gabriel-Welsch multiple range test used for means separations.

[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

[x] Contrasts include both VRA treatments in 2006 at both sites

[w] Data from Scott 2006 analyzed as a completely randomized design

na – Treatment not included at this site-year.

The mean YP estimates based on the empirical YP equations and in-season NDVI measurements of the NR treatments ranged from 2466 – 3877 kg ha^{-1}, depending on the site-year and YP equation used (Table 4.8). The lowest maximum estimated YP was at Indian Head in 2005, where the overall NDVI values were low relative to the other site-years. Table 4.8 shows the relatively optimistic YP estimates derived using VRA2 relative to VRA1. However, the YP estimates of the NR and VRA2 treatments are equally optimistic; thus, the N recommendations were comparable to those recommended using VRA1. With all other factors being equal, the rates recommended using VRA2 are simply 33% greater than those recommended for the same plots with VRA1.

Table 4.8. Estimated yield potentials (kg ha^{-1}) and estimated post-emergent N requirements (kg N ha^{-1}) of canola in the VRA treatments as well as total N fertilizer savings in this treatment relative to the FP treatment within the same site-year.

		Indian Head			Scott		
		2005	**2006**		**2005**	**2006**	
		na	VRA1	VRA2	na	VRA1	VRA2
		days					
Days from Planting[z]		44	45		36	43	
		˚C					
GDD[y]		539	612		439	588	
		kg ha^{-1}					
Estimated YP[x]	NR	2466	2691	3579	3877	2739	3642
	VRA	2387	2467	3283	3840	2587	3436
	Diff.	79	224	296	37	152	206
N Recommended[w]	Mean	6	15	20	4	10	14
	Min	0	0	4	0	0	7
	Max	11	29	40	11	22	22
N savings[v]	Mean	53	43	39	56	24	20
	Min	48	29	18	49	12	12
	Max	59	58	54	57	34	27

[z] Number of days between seeding and sensing
[y] GDD (base temperature 0 ˚C) accumulated between seeding and sensing
[x] Mean estimated yield potential using NDVI/GDD and most current YP equation for the period (Figure 4.1)
[w] Post-emergent N rate recommended for canola plots in the VRA treatment using YP estimates and N application algorithm (Equation 4.1)
[v] Total quantity of N fertilizer applied in the VRA treatment subtracted from the rate applied in FP treatment
na – Only one VRA treatment was included in 2005, which is directly comparable to VRA2 in 2006

The greatest estimated potential response to PE N was at Indian Head in 2006, where a 9% increase in yield was predicted using the algorithm. The smallest was at Scott in 2005, where only a 1% potential increase was predicted with the addition of PE N. It is questionable whether such small yield responses to PE N would be sufficient to justify PE N applications at all. The average potential savings in N fertilizer for the VRA treatments ranged from 20 – 56 kg N ha^{-1} and within each site-year and algorithm, the recommended N rates varied by 10 – 36 kg ha^{-1}. As previously suggested, the average recommended rates of 6 kg N ha^{-1} at Indian Head in 2005 and 4 kg N ha^{-1} at Scott in 2005 would not likely be worth applying, considering the costs.

4.4.3 Grain Yield, N Uptake and Fertilizer N-Use Efficiency

Nitrogen management affected canola grain yields at all site-years. As predicted by the NDVI measurements, canola always responded well to fertilizer, with the unfertilized check yielding lower than the combined fertilized treatments at all site-years (Table 4.9). Mean grain yields of the check plots ranged from 992 – 2087 kg ha^{-1} and were 61 – 68% of the yields of the highest yielding fertilized treatment. There were no instances where the NR treatment yielded significantly higher than the FP treatment, indicating that 100 – 116 kg fertilizer N ha^{-1}, or approximately 150 kg total N ha^{-1} was sufficient to maximize canola yields in this study. At Indian Head, the NR treatment yielded higher than both the RN and FP treatment in 2006 but not in 2005.

While there was no definitive evidence of a yield response to PE N at any of the site-years, at Scott 2006 the SF treatment had the highest mean yield of all the treatments. However, with no RN treatment at Scott to compare to, we cannot say with certainty that there was a response to PE N at this site. At Indian Head, the RN treatment yielded the same as the SF and VRA treatments in both years, indicating that there was no yield response to PE N. In 2005 at Indian Head, because the RN treatment also yielded the same as the FP treatment, we attributed the apparent lack of response to PE N in the SF and VRA treatments to nearly sufficient N at the reduced rates of starter N.

Table 4.9. Grain yields (kg ha^{-1}) of canola grown under various N management strategies at Indian Head and Scott in the 2005 and 2006 growing seasons.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management	kg ha^{-1}			
Check	2087b	1481d	1713c	992b
N Rich (NR)	3052a	2312ab	2550a	1419a
Farmer Practice (FP)	2958a	2389a	2294ab	1479a
Reduced N (RN)	2731a	2014bc	na	na
Split / Fixed (SF)	2718a	2000bc[y]	2271ab	1543a
Variable Rate 1 (VRA1)	na	1935c	na	1402a
Variable Rate 2 (VRA2)	2776a	2019bc	2095bc	1328a
	Analysis of Variance			
Source	p > F			
Treatment	**<0.001**	**<0.001**	**0.003**	**<0.001**
Replicate	0.354	0.086	0.133	[v]
Residual C.V. (%)	6.5	7.7	10.0	10.3
	Selected Contrasts			
	p-value			
Check vs Rest	**<0.001**	**<0.001**	**<0.001**	**<0.001**
NR vs RN+SF+VRA[x]	**0.008**	**0.002**	**0.022**	0.949
FP vs RN+SF+VRA[x]	**0.050**	**<0.001**	0.437	0.506
VRA vs NR[w]	**0.042**	**0.002**	**0.021**	0.539
VRA vs FP[w]	0.162	**<0.001**	0.882	0.201
VRA vs SF[w]	0.653	0.811	0.322	0.054
VRA vs RN	0.723	0.702	na	na

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc) with the Ryan-Einot-Gabriel-Welsch multiple range test used for means separations.
[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment
[x] RN treatment excluded from contrast at Scott
[w] Contrasts include both VRA treatments in 2006 at both sites
[v] Data from Scott 2006 analyzed as a completely randomized design
na – Treatment not included at this site-year

That both the NR and FP treatments yielded higher than the combined reduced / split N treatments at Indian Head 2005 suggests that N availability limited grain yields in these treatments to some extent at this site-year. In 2006 at Indian Head, the FP treatment yielded 376 kg ha^{-1} higher than the RN treatment and the RN, SF, and VRA treatments yielded the same as one another. The extremely dry conditions following the PE N applications likely restricted the movement of the UAN, resulting in increased potential for volatile losses (Whitehead and Raistrick 1991) and reduced plant uptake of the applied N. In previous work completed at Indian Head and Scott, SK, Holzapfel et al. (2007a) showed that PE UAN is not an effective method of supplying N to crops when prolonged dry periods follow the application.

While the VRA treatment at Scott in 2005 did not yield significantly different from either the SF or FP treatments, it yielded lower than the NR treatment and there was an overall tendency for the plots that received higher rates of fertilizer N to yield higher. Despite the fact that there was no difference in NDVI between the two treatments, the NR treatment yielded 455 kg ha^{-1} higher than the VRA treatment. Recall that the plots at this site were severely damaged by wind and hail while in full bloom. While only speculation, it is conceivable that the additional vegetative growth required for the plots to recover from the hail damage, growth that would not have been required had the plots not been damaged, increased the plant's total N requirements. As such, the additional fertilizer N applied in the NR treatment may have allowed the crop in this treatment to recover from the hail damage more fully than the treatments that received less N. While the VRA treatment received 24 kg ha^{-1} less fertilizer N than the FP treatment at Scott in 2005 and the two treatments did not yield differently from one another, it appeared that YP was not maximized in either treatment. At Scott in 2006, the VRA treatments yielded the same as the FP and NR treatments, but lower than the SF treatment, again possibly indicating that yield was not maximized in the VRA treatment.

In 2006, where we tested the two variations of the algorithm, there was no apparent advantage to adjusting the YP equation upwards by 33%. While the PE N rates applied in the adjusted curve (VRA2) were 4 – 5 kg N ha^{-1} higher than those recommended using VRA1, the two treatments yielded the same at both sites. As such, there was no evidence that adjusting the YP curves upwards improved the estimates of PE N requirements and we have no reason to recommend the adjustment.

Nitrogen management affected grain N content at three of the four site-years (Table 4.10). Excluding Scott 2005, where grain N was determined using an NIR instrument, mean grain N content ranged from 30.6 – 37.8 g N kg grain^{-1}, which is comparable to values reported in previous research (Hocking et al. 2002; Malhi and Gill 2007). At Scott in 2005, the values ranged from 40.0 g N kg grain^{-1} in the VRA treatment to 42.3 g N kg grain^{-1} in the NR treatment. The NR treatment had the highest mean grain N content at all site-years and was significantly higher than any other individual treatments at Indian Head in 2006. The grain N content of the NR treatment was always significantly higher than that of the split / reduced N treatments while that of the FP treatment was only greater than the split / reduced N treatments at Indian Head in 2006, suggesting that fertilizer N does not greatly affect grain N until fertilizer rates exceed those required for maximum grain yields.

Grain N in the unfertilized check treatment was lower than that of the combined fertilized treatments at both sites in 2006. Malhi and Gill (2007) found that fertilizer N did not typically cause grain protein content to increase until the N rates approached 75 – 100 kg N ha^{-1}. Furthermore, low rates of fertilizer N can cause grain protein content to decrease in some cases, presumably because of a dilution effect caused by the increase in grain yields (Malhi and Gill 2007). In other research, grain N increased linearly with N rate beyond rates of 40 kg N ha^{-1} (Malhi and Gill 2004) and increases in grain N haves been reported at fertilizer rates as low as 25 kg N ha^{-1} (Hocking et al. 2002).

Table 4.10. Grain N (g N kg grain^{-1}) of canola grown under various N management strategies at Indian Head and Scott in the 2005 and 2006 growing seasons. Grain N was determined using the Kjeldahl method at all site-years except for Scott 2005 where an NIR instrument was used.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management	g N kg^{-1}			
Check	33.7	31.9cd	40.6bc	30.6c
N Rich (NR)	37.1	37.8a	42.3a	37.0a
Farmer Practice (FP)	34.5	34.8b	40.7bc	35.2ab
Reduced N (RN)	32.9	33.9bc	na	na
Split / Fixed (SF)	35.8	31.8cd[y]	41.2ab	36.6a
Variable Rate 1 (VRA1)	na	31.3d	na	33.3b
Variable Rate 2 (VRA2)	33.9	32.6cd	40.0c	33.3b
	Analysis of Variance			
Source	p > F			
Treatment	0.088	**<0.001**	**0.008**	**<0.001**
Replicate	0.386	**0.002**	**<0.001**	[v]
Residual C.V. (%)	5.8	2.81	1.58	2.82
	Selected Contrasts			
	p-value			
Check vs Rest	0.311	**0.002**	0.274	**<0.001**
NR vs RN+SF+VRA[x]	**0.023**	**<0.001**	**0.002**	**<0.001**
FP vs RN+SF+VRA[x]	0.768	**<0.001**	0.815	0.157
VRA vs NR[w]	**0.039**	**<0.001**	**0.001**	**<0.001**
VRA vs FP[w]	0.668	**<0.001**	0.206	**0.005**
VRA vs SF[w]	0.209	0.864	**0.042**	**<0.001**
VRA vs RN	0.474	**0.003**	**0.001**	na

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc) with the Ryan-Einot-Gabriel-Welsch multiple range test used for means separations.

[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

[x] RN treatment excluded from contrast at Scott

[w] Contrasts include both VRA treatments in 2006 at both sites

[v] Data from Scott 2006 analyzed as a completely randomized design

na – Treatment not included at this site-year.

Applying N fertilizer consistently increased the quantity of N removed in the seed with the unfertilized check always removing less grain N than the fertilized treatments (Table 4.11). Absolute quantities of N removed in the canola seed ranged from 30 kg N ha^{-1} at Scott in 2006 up to 113 kg N ha^{-1} at Indian Head in 2005 and the patterns of grain N removal resembled those observed for grain yield (Table 4.9). The most N tended to be removed by canola seed in the NR treatment at all site-years except Scott 2006, where

N removal was highest in the SF treatment, which also yielded the highest. However, the quantity of grain N removed in the NR treatment was never significantly higher than for the FP treatment, suggesting that the crop was not utilizing much of the additional N fertilizer. Aside from being lost, the N not accounted for could be incorporated into crop residues, soil organic matter (Halvorson et al. 1999), and the soil's inorganic N pool (Smith et al. 1988; Sogbedji et al. 2000).

Table 4.11. Nitrogen removed (kg N ha^{-1}) in the grain of canola grown under various N management strategies at Indian Head and Scott in 2005 and 2006. Grain N was determined using the Kjeldahl method at Indian Head and Scott in 2006 with an NIR instrument used at Scott in 2005.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management	kg N ha^{-1}			
Check	70.1c	47.3c	69.7c	30.4c
N Rich (NR)	113.2a	87.6a	107.6a	52.6ab
Farmer Practice (FP)	102.2ab	83.4a	93.7ab	52.1ab
Reduced N (RN)	89.8b	68.1b	na	na
Split / Fixed (SF)	97.2b	63.7b[y]	93.6ab	56.4a
Variable Rate 1 (VRA1)	na	60.3b	na	46.8ab
Variable Rate 2 (VRA2)	94.1b	65.8b	84.3bc	44.2b
	Analysis of Variance			
Source	p > F			
Treatment	**<0.001**	**<0.001**	**0.001**	**<0.001**
Replicate	0.524	0.186	**0.035**	[v]
Residual C.V. (%)	7.8	9.8	9.9	11.2
	Selected Contrasts			
	p-value			
Check vs Rest	**<0.001**	**<0.001**	**<0.001**	**<0.001**
NR vs RN+SF+VRA[x]	**<0.001**	**<0.001**	**0.007**	0.275
FP vs RN+SF+VRA[x]	0.062	**<0.001**	0.419	0.347
VRA[w] vs NR	**0.002**	**<0.001**	**0.006**	**0.042**
VRA vs FP	0.137	**<0.001**	0.201	0.057
VRA vs SF	0.561	0.882	0.202	**0.003**
VRA vs RN	0.423	0.228	na	na

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc) with the Ryan-Einot-Gabriel-Welsch multiple range test used for means separations.
[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment; [x] RN treatment excluded from contrast at Scott; [w] Contrasts include both VRA treatments in 2006 at both sites; [v] Data from Scott 2006 analyzed as a completely randomized design; na – Treatment not included at this site-year.

Nitrogen management significantly affected fall residual NO_3-N levels for the zero to 60 cm soil depth at Indian Head in both years of the study and at Scott in 2006 only (Table 4.12). While the data from Scott in 2005 was highly variable, the mean fall residual NO_3-N levels of both the SF and NR treatments tended to be higher than for any other treatments. Because of the high N application rates, residual NO_3-N levels in the NR treatment at Indian Head were always much higher than any of the other treatments. Residual NO_3-N levels of the VRA and FP treatments tended to be similar to each other and the levels of the FP treatment were never higher than the combined split / reduced N treatments, indicating that fall soil NO_3-N does not accumulate until N rates well beyond those required for maximum yield are applied. This in agreement with Smith et al. (1988) where although increasing N rates from 20 – 100 kg N ha^{-1} had little effect on soil NO_3-N levels in the zero to 50 cm soil profile, further increases to 200 kg N ha^{-1} greatly increased residual NO_3-N levels. Residual NO_3-N levels in the SF treatment tended to be higher than in the VRA treatments, although the difference was generally not significant.

While the temperate climate of the Canadian Prairies is not especially conducive to NO_3^- leaching or denitrification under continuously cropped conditions, substantial losses can occur at localized sites, especially during the uncropped period between harvest and the establishment of the subsequent crop (Campbell et al. 1984; Di and Cameron 2002). In general, the potential for NO_3-N leaching is greatest on coarse textured, sandy or loamy soils while the potential for denitrification is greatest in fine-textured, clay soils (Sogbedji et al. 2000**).** Nitrate losses often occur in depressional landscape positions during the early spring snowmelt period. During this period, pooling of meltwater provides the prolonged supersaturated conditions that can result in deep leaching and groundwater contamination (Di and Cameron 2002) and the anaerobic or partly anaerobic conditions conducive to denitrification and N_2O release (Lemke et al. 1998). In southern Manitoba, Tiessen et al. (2005) found that fall-banded urea was not as effective as spring banded urea in the lower landscape positions, but both application times were equally effective in the higher landscape position.

Table 4.12. Quantity of residual NO_3-N (kg N ha^{-1}) remaining in the zero to 60 cm soil profile after harvest for canola plots managed under various N management strategies at Indian Head and Scott in 2005 and 2006.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management	kg NO_3-N ha^{-1} 0 - 60cm			
Check	20.7b	13.6b	22.7	11.2a
N Rich (NR)	59.7a	47.2a	42.0	15.4a
Farmer Practice (FP)	28.7b	16.9b	24.1	9.8a
Reduced N (RN)	24.7b	13.7b	na	na
Split / Fixed (SF)	33.5b	17.4b[y]	40.3	15.7a
Variable Rate 1 (VRA1)	na	13.2b	na	11.5a
Variable Rate 2 (VRA2)	28.8b	15.4b	25.4	10.1a
	Analysis of Variance			
Source	$p > F$			
Treatment	**<0.001**	**<0.001**	0.175	**0.029**
Bloc	0.221	0.915	0.216	y
Residual C.V. (%)	21.1	33.0	43.9	23.6
	Selected Contrasts			
	p-value			
Check vs Rest	**0.002**	0.060	0.202	0.427
NR vs RN+SF+VRA[x]	**<0.001**	**<0.001**	0.303	0.091
FP vs RN+SF+VRA[x]	0.935	0.593	0.324	0.135
VRA vs NR[w]	**<0.001**	**<0.001**	0.138	**0.018**
VRA vs FP[w]	0.986	0.518	0.904	0.587
VRA vs SF[w]	0.340	0.436	0.114	**0.013**
VRA vs RN	0.883	0.417	na	na

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc) with the Ryan-Einot-Gabriel-Welsch multiple range test used for means separations.

[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

[x] RN treatment excluded from contrast at Scott

[w] Contrasts include both VRA treatments in 2006 at both sites

[v] Data from Scott 2006 analyzed as a completely randomized design

na – Treatment not included at this site-year.

Agronomic NUE is the difference between the grain yields of a fertilized crop and an unfertilized crop divided by the quantity of N fertilizer applied (Fageria and Baligar 2003; Fageria and Baligar 2005). Overall, ANUE was higher at Indian Head than at Scott, presumably because of higher grain yields and greater response to fertilizer N at this site (Table 4.13). The observed ANUE values fell within the ranges of values for canola reported in other studies, ranging from as low as 2.8 kg kg^{-1} at Scott in 2006 up to 15.7 kg kg^{-1} at Indian Head in 2005. Under rainfed conditions in Australia, Smith et al. (1988) reported ANUE for canola ranging from 4 – 10 kg kg^{-1}, while under irrigation ANUE ranged from 7 – 21 kg kg^{-1}. In a separate study completed at several sites in southern New South Wales, ANUE ranged from 9.5 – 15.9 kg kg^{-1} at a fertilizer rate of 10 kg N ha^{-1} to 0.6 – 14.0 kg kg^{-1} when 75 kg N ha^{-1} of fertilizer was applied (Hocking et al. 2002). In Argentina, ANUE of spring canola growing under varying N availabilities ranged from 6.0 kg kg^{-1} at 120 kg fertilizer N ha^{-1} to 19.3 kg kg^{-1} when 30 kg N ha^{-1} was applied (Chamorro et al. 2002). While ANUE values for canola grown specifically in the Canadian Prairies were not found in the literature, Johnston et al. (1997) showed that recovery of fertilizer N (grain plus straw) by canola in Saskatchewan and Alberta ranged from 15 – 50% and typically decreased with increasing N rates.

Nitrogen management significantly affected canola ANUE at Indian Head in both years but not at Scott. For the site-years where the overall F-test was significant for the effects of N management, the mean ANUE was lowest for the NR treatments and highest for the RN treatments. At Indian Head, ANUE of the NR treatment was significantly lower than the combined split / reduced N treatments in both years. In 2005 at Indian Head, the observed ANUE values were the same for the VRA and RN treatments and both were higher than for any of the other treatments. In 2006 at Indian Head, ANUE of the VRA treatment was not significantly different from either the RN or the FP treatments. However, even though the VRA and FP treatments had similar ANUE, the efficiency of the FP treatment was achieved at a higher grain yield and with more fertilizer N than for the VRA treatment; thus the FP treatment would have been more feasible from a producer's perspective.

Table 4.13. Agronomic N use efficiency (kg grain yield kg fertilizer N applied^{-1}) for canola grown under various N management strategies at Indian Head and Scott in 2005 and 2006.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management	kg kg^{-1}			
N Rich (NR)	4.8c	4.3b	3.9	2.8
Farmer Practice (FP)	8.7bc	8.6ab	5.0	4.1
Reduced N (RN)	15.7a	11.2a	na	na
Split / Fixed (SF)	6.3c	6.4ab	4.8	5.7
Variable Rate 1 (VRA1)	na	8.1ab	na	4.7
Variable Rate 2 (VRA2)	14.7ab	8.5ab	6.5	4.9
	Analysis of Variance			
Source	p > F			
Treatment	**0.002**	**0.041**	0.369	0.432
Replicate	0.112	**0.025**	0.375	[v]
Residual C.V. (%)	33.4	33.6	39.5	47.5
	Selected Contrasts			
	p-value			
NR vs RN+SF+VRA[x]	**0.003**	**0.012**	0.189	0.084
FP vs RN+SF+VRA[x]	0.093	0.999	0.605	0.429
VRA vs NR[w]	**0.001**	**0.026**	0.121	0.151
VRA vs FP[w]	**0.026**	0.894	0.345	0.601
VRA vs SF[w]	**0.004**	0.239	0.290	0.499
VRA vs RN	0.683	0.097	na	na

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc) with the Ryan-Einot-Gabriel-Welsch multiple range test used for means separations.

[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

[x] RN treatment excluded from contrast at Scott

[w] Contrasts include both VRA treatments in 2006 at both sites

[v] Data from Scott 2006 analyzed as a completely randomized design

na – Treatment not included at this site-year.

At Scott, while the overall F-test for the effect of N management was not significant in either year, the NR treatment always tended to have the lowest mean ANUE and the VRA and SF treatments tended to have the highest ANUE in 2005 and 2006 respectively. The variability within the treatments tended to be very high for ANUE, with coefficients of variation ranging from 33.4 to 47.5%; thus, differences between treatments were difficult to detect. Overall, these results are consistent with those of other studies for canola where agronomic efficiency or N use efficiency peaked at low to intermediate N rates and tended to be lowest at high N rates (Smith et al. 1988; Johnston et al. 1997; Chamorro et al. 2002; Hocking et al. 2002).

4.5 CONCLUSIONS

While the results from these four site-years do not allow us to draw definitive conclusions regarding the long-term feasibility of sensor-based N management practices for canola, they illustrate some of the environmental scenarios where using this technology is likely to be beneficial as well as those where it is likely to fail. At Indian Head in 2005, where the response to N fertilizer rates beyond 40 kg N ha^{-1} was minimal, using sensor-based estimates of PE N requirements to determine PE N rates greatly reduced fertilizer N inputs with minimal yield losses. The mean ANUE of the VRA treatment at Indian Head in 2005 tended to be substantially lower than that of the FP treatment, however the difference was not statistically significant. At Indian Head in 2006, however, the environmental conditions presented a worst-case scenario for sensor-based N management, and the VRA treatment performed poorly relative to the FP treatment. Favourable growing conditions early in the season at Indian Head resulted in a strong response to fertilizer N applied early in the season, which was evident in the NDVI measurements taken during this period. However, the drought that followed the PE N applications presumably lowered the overall canola YP and prevented the crop from utilizing the surface applied N and, consequently, there was no yield response to PE N. Thus, at Indian Head in 2006, the benchmark FP treatment was the most feasible.

The results from Scott were somewhat less conclusive than at Indian Head, possibly because the hail damage that occurred in both years created uncertainty in the practical value of the results. While the VRA performed equally as well as the FP treatment at Scott in 2005, grain yield was not maximized in either of these two treatments. Furthermore, the mid-season NDVI measurements provided no indication of the observed yield response to high rates of N. In 2006 at Scott, the VRA treatments performed reasonably well, with both the VRA1 and VRA2 treatments yielding the same as the NR and FP treatments, despite having received less fertilizer N in total. Nonetheless, that the SF treatment had the highest mean overall yield may indicate that the N fertilizer application algorithm underestimated the N requirements in the VRA treatments at Scott 2006, perhaps due to the hail damage.

The N application algorithm proposed in this research has an important limitation that should be acknowledged. The calculations used to estimate PE N requirements assumed that the upper yield potential of each plot in each replicate or study area (depending on the site-year) would be equal if N were not limiting. On a field scale, this is to say that all of the observed variability in NDVI for a field is a result of differences in N availability and, furthermore, that these differences can be completely corrected with PE N. In the case of highly variable landscapes or fields with non-uniform plant populations, this will almost certainly not be the case. Canola YP diminishes when plant populations fall below 20 plants m^{-2} (Angadi et al. 2003), thus if isolated parts of a field have populations this low, it is conceivable that they would not respond to N fertilizer in the same manner as areas where plant populations are higher. Furthermore, Brandt et al. (2007) showed that plant densities must be high for canola to maximize the potential benefit of high N rates. Variability in soil moisture content could present similar problems in variable landscapes whereby N requirements of potentially moisture limited upper landscape positions will not likely be the same as in higher moisture, lower landscape positions (Pennock et al. 2001). The upshot is that the methods used in this study should be suitable in reasonably level fields with uniform overall YP and plant populations, but may not be so if these assumptions are not met. It is probable that the methods described by Raun et al. (2005) would more accurately estimate potential response to PE N across variable landscape positions or plant populations. These methods utilize a response index calculated by dividing the mean NDVI of a high N pass by the mean NDVI of the adjacent pass to estimate the average response to PE N across the range of potential estimated YP (Raun et al. 2005). The maximum YP for a field is determined using the lesser of the YP estimated using the maximum observed NDVI in the field or an arbitrary maximum biological YP for the crop (Raun et al. 2005).

An important obstacle to the adoption of this technology by producers is the added cost of applying PE N as well as the additional strains on labour and equipment associated with applying PE N over a large number of acres. Post-emergent N applications can potentially interfere with herbicide and/or fungicide applications and wet conditions could altogether prevent the timely application of PE N. In terms of cost alone, increases in profit resulting from the use of this technology must be sufficient to cover the cost of the PE N application for sensor based N management to be economically feasible. While circumstances could certainly change with the imposition of environmental regulations limiting either allowable consumption of fertilizer N or residual levels of soil mineral N, it is arguably less costly for producers to apply too much fertilizer N than too little under the current economic conditions. Perhaps reserving the use of this technology for identifying opportunities where above average yields are possible with PE N rather than instinctively trying to reduce N rates would be a more feasible option for producers. In addition, doing so would effectively reduce the number of acres over which PE N would have to be applied in a given year and reduce the risks of yield losses under drought conditions. Firmly establishing the economic feasibility of sensor-based N management practices requires that data be collected over a large number of years for a variety of crops and the results applied to a wide range of economic scenarios.

4.6 ACKNOWLEDGMENTS

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5.0 VARIABLE RATE NITROGEN APPLICATIONS IN CANOLA USING SENSOR-BASED ESTIMATES OF YIELD POTENTIAL AND RESPONSE TO POST-EMERGENT NITROGEN: A LARGE-SCALE EVALUATION USING COMMERCIAL EQUIPMENT

5.1 ABSTRACT

The adoption of more reliable methods of matching N inputs with crop requirements is one potential means by which N application practices in western Canada could conceivably be improved upon. Nine on-farm field trials using commercial field equipment were completed with canola (*Brassica napus* L.) to establish whether variable rate applications of post-emergent (PE) N to canola, with PE N rates determined using NDVI measurements and an N application algorithm, is a feasible alternative to the traditional practice of banding a fixed rate of N fertilizer at seeding. When canola was between the early bolting stage and the start of flowering, NDVI tended to increase with the rate of N applied at seeding at the majority of the sites, suggesting that NDVI used along with N rich references was a good indicator of N status in canola. The total applied N rates in the variable rate treatments ranged from 29% less to 14% higher than the benchmark treatments where fixed rates of N were applied. Nitrogen fertilizer use was reduced in the variable rate treatment at five sites, increased at three sites, and essentially the same at one site. In all but two site-years, where the canola in the variable rate treatment yielded higher than the benchmark treatment, the grain yields of the two treatments were not significantly different from one another. For this technology to be feasible, however, increases in revenues must be sufficient to cover the added cost of the PE N application and this often was not the case in the current study. While sensor-based N management in canola appears to be viable overall, based on these results we would not recommend reducing N rates at seeding below what is required to produce average

yields. Still, optical sensing technology may have potential as tool to identify situations where there is potential to increase grain yields sufficiently with post-emergent N to justify the added application costs and labour requirements.

5.2 INTRODUCTION

Nitrogen is the nutrient that most commonly limits crop growth (Havlin et al. 2005) and is applied as fertilizer in greater quantities than any other nutrient (Korol 2002). In 2001/2002, more than 1.5 million tonnes of inorganic N were sold in Canada, with more than 80% attributable to the prairies (Korol 2002). While world-wide estimates of fertilizer nitrogen use efficiency (NUE) are as low as 33% (Raun and Johnson 1999), recovery of fertilizer may be as high as 70% in the relatively temperate Canadian Prairies, though possibly not all in the year of application (Malhi et al. 2001; Krupnik et al. 2004). Furthermore, the adoption of banding as the predominant application method for N fertilizer in western Canada (Harapiak et al. 1993) has likely enhanced NUE in these regions relative to many other parts of the world. Developing and adopting improved methods for matching N inputs with crop requirements on a site-year specific basis is one way in which NUE in the Canadian prairies may be increased beyond current levels (Raun and Johnson 1999).

The quantity of fertilizer N that crop's require depends on several factors which may be broadly categorized to include yield potential (YP), the soil's capacity to supply N, and anticipated losses of applied N. However, the spatial and temporal variability of each of these factors renders decisions regarding fertilizer N rates difficult to make with certainty.

The YP of crops is the culmination of the relationship between many abiotic and biotic factors. Some of the factors, such as competition from pests, genetics, and nutrient availability are largely a function of management, while others, notably moisture availability and temperature, are generally beyond the control of producers. Over much of the northern Great Plains, potential evapotranspiration exceeds total precipitation and, as such, moisture availability is often the most important factor limiting dryland canola yields in these regions (Johnston et al. 2002). In areas such as southwest Saskatchewan, where the water deficit is especially high, adequate spring soil moisture is critical for successful canola production (Angadi et al. 2004). However, soil moisture availability varies across the landscape and, at least under dry conditions, both grain yields and N requirements tend to be higher in concave versus convex landscape positions (Pennock et al. 2001). While Pennock et al. (2001) stress the importance of spring soil moisture in determining N requirements, growing season precipitation is often also important (Brandt and McGregor 1997) and accounts for much of the annual water use of crops (Lafond et al. 2006). Unfortunately, growing season precipitation cannot be predicted early enough or at a fine enough spatial resolution to be useful for generating fertilizer recommendations (Campbell et al. 1997) thus recommendations can only be generated using a risk approach with precipitation probability based on long term observations (Westco Agronomy Services 2004). Extreme temperatures affect canola growth in that daytime temperatures exceeding 29˚C during flowering and pod filling can severely depress seed yields (Angadi et al. 2000; Morrison and Stewart 2002).

The soil's ability to supply N is the second major factor that must be considered when determining N fertilizer requirements. The quantity of N that the soil can supply depends on both the quantity of plant available residual soil N prior to seeding as well as any organic N mineralized throughout the growing season. While estimating residual NO_3^- levels for fields using composite soil samples and analyses is a widely accepted and recommended practice, it does not account for within field spatial variability. In seven out of eight Missouri cornfields, using composite soil tests as a basis for determining N fertilizer rates resulted in more than half of each field being over or under fertilized by 34 kg N ha^{-1} and more than one-fifth being off-target by 65 kg N ha^{-1} or more (Scharf et al. 2005). A second limitation of traditional, composite soil tests is that they provide no indications of the soil's potential for mineralizing N. While several organic N fractions, including amino sugar N (Mulvaney et al. 2001), hot KCl extractable N (Jalil et al. 1996), and Illinois Soil Test N (Khan et al. 2001), have shown potential as indicators of mineralizable N, these tests are not currently used in commercial testing facilities. Furthermore, the extent to which organic N is mineralized also depends on environmental factors such as soil moisture content (Campbell et al. 1999), soil temperature (Campbell et al. 1984), and soil wetting and drying cycles (Miller et al. 2005), all of which are variable and difficult to predict.

The last major factor to consider when deciding how much N to apply is the anticipated efficiency of the applied fertilizer. The efficiency of applied N depends primarily on the placement and timing of the fertilizer application as the various N sources perform similarly when managed accordingly (Grant et al. 2002). In terms of placement, banding is typically the most efficient method of applying N fertilizer and often results in increased grain yields relative to surface applications (Harapiak et al. 1993; Grant et al. 2002; Havlin et al. 2005). Banding is the predominant method of applying N fertilizer in western Canada, with 75 – 80% of producers already using some form of band application in 1992 (Harapiak et al. 1993). With respect to timing, spring applications of N fertilizer generally result in equal or greater canola yields compared with fall applied N, although fall applications of NO_3^- fertilizers should be avoided altogether (Grant et al. 2002). The general premise is that applying N fertilizer as close to the time of plant uptake as possible leaves less time for immobilization or other losses of N to occur. Environmental factors also affect the efficiency of N fertilizer and can cause variation in NUE across the landscape. In Manitoba, Tiessen et al. (2005) observed lower recovery of fall applied NH_3 in depressional areas than in higher landscape positions within the same field, likely a result of greater denitrification losses in the depressional areas during the spring snowmelt period.

The rationale behind site-specific management is to address sources of variability by "matching resource applications and agronomic practices with soil and crop requirements as they vary over space and time (Whelan and McBratney 2000)". While it is broadly accepted that N fertilizer requirements are variable in fields, how such variability should be addressed is less certain.

Much of the early research with precision agriculture strived to develop methods to assess spatial variability in soil parameters and determine how these parameters could be used to explain variability in grain yields. Substantial efforts focussed on developing soil sampling strategies (Franzen et al. 1998; Rains et al. 2001; Chang et al. 2003) and interpolation methods for mapping soil parameters (Wollenhaupt et al. 1997; Kravchenko and Bullock 1999). The difficulty with this approach is that spatial variability in N fertility can be very high (Solie et al. 1999), often making soil sampling to describe spatial variability in soil parameters uneconomical and impractical.

Remote sensing techniques provide a more cost and labour-effective method of measuring within field variability than soil sampling. Colour aerial photographs of bare soil (Fleming et al. 2004), electrical conductivity maps (Johnson et al. 2003; Fleming et al. 2004), and multispectral satellite imagery (Boydell and McBratney 2002; Basnyat et al. 2005) have all been used to identify distinct management zones within fields. However, such methods often require complex algorithms and image processing with specialized software and are generally incapable of accounting for temporal variability in management zones.

More recently, ground-based sensors that utilize an active light source, such as the GreenSeeker^{TM} (NTech Industries) and Crop Circle^{TM} (Holland Scientific) have been developed and made commercially available. These sensors are advantageous over satellite mounted sensors in that they are unaffected by satellite return cycles, the position of the sun, or atmospheric conditions. Perhaps the greatest advantage of the GreenSeeker^{TM} sensor is that it is readily integrateable with fertilizer application equipment and used to direct variable rate N applications in real time. This capability effectively eliminates the need for delineating management zones, developing fertilizer prescription maps and, if mapping is not required, global positioning systems (GPS) for implementing of site-specific fertilizer applications.

Researchers at Oklahoma State University's (OSU) Stillwater campus have been instrumental in developing the GreenSeeker^{TM} sensor along with the methods for using this technology to estimate N requirements. Early work at OSU demonstrated that NDVI measurements of winter wheat canopies could be used to estimate yield potential during the growing season (Raun et al. 2001; Raun et al. 2002). In their first attempts to estimate the potential grain YP of winter wheat, Raun et al. (2001) explained more than 80% of the observed variability in grain yields by dividing the sum of two post-dormancy NDVI measurements by the number of growing degree days (GDD) accumulated between the two measurements. Raun et al. (2002) later refined their methods so that only one NDVI measurement, which they subsequently divided by the number of days between planting and sensing where GDD was greater than zero, was required to estimate winter wheat YP.

To estimate the potential response of winter wheat to post-emergent N, Raun et al. (2002) proposed using an N-rich reference strip to estimate the maximum YP for a field under non-N limiting conditions relative to that of the crop under evaluation. As further justification for this approach, Mullen et al. (2003) showed that the ratios of NDVI measurements of wheat growing in contrasting N fertility environments and those of the observed grain yields in the same two environments were linearly related to one another. In this manner, Raun et al. (2002) increased revenues and NUE compared with traditional N management practices, either by maintaining yields using less fertilizer N or increasing relative yields with PE when there was opportunity to do so. Fertilizer NUE of the sensor-based treatments ranged from equal to more than 15% greater than each of the treatments where predetermined, uniform rates of N were applied (Raun et al. 2002). Raun et al. (2005) describe the N application algorithms developed at OSU in detail.

While previous research has shown that canola often responds well to PE, surface dribble banded (SDB) urea ammonium-nitrate (UAN), delaying N applications can be risky, especially when no starter N is applied (Holzapfel et al. 2007). More recent work has shown that if 50 – 66% of a canola crop's total N requirements are supplied at seeding, the remainder can be applied during the bolting stage without forgoing grain yield (Lafond et al. 2007). Applying a portion of a crop's N requirements at the time of seeding and the remainder part way through the growing season gives producers the opportunity to assess growing conditions partway through the season and make better informed decisions as to whether or not a crop will benefit from additional N inputs (Holzapfel et al. 2007; Lafond et al. 2007). Used along with N rich reference strips (Raun et al. 2002), active optical sensors such as the GreenSeeker^{TM} have potential as a tool to help producers decide whether or not to apply PE N in a more reliable and objective manner than previously possible.

The objective of this study was to evaluate the effectiveness of using NDVI measurements and N rich reference strips to direct PE variable rate applications of UAN for canola compared with the practices of applying all fertilizer N at seeding and split N applications using fixed rates. We conducted these experiments in cooperation with local producers using commercial equipment, which enabled us to evaluate these methods over varying conditions while at the same time helping to familiarize producers with this developing technology. Furthermore, conducting these experiments using commercial equipment allowed us to identify some of the immediate challenges that producers may face when adopting this technology.

5.3 MATERIALS AND METHODS

5.3.1 Treatment descriptions

The treatments evaluated were several N management strategies where the rates, timing, and in certain instances, forms of N fertilizer were varied. The cooperating producers chose the absolute N rates applied, with 100% being the rate applied to the non-study areas of each field. The following four treatments were included at each of the experimental sites: 1) Farmer Practice (FP), where all fertilizer N was applied at approximately the time of seeding at the 100% rate, 2) N-Rich (NR), where all fertilizer N was applied at approximately the time of seeding at a rate that was 133 – 150% of that applied in the FP treatment, 3) Split application / Fixed rate (SF), where 66% of the rate applied in the FP treatment was applied at the time of seeding and 34% was applied as a PE surface-dribble band of UAN, and 4) Variable Rate Application (VRA), where 66% of the rate applied in the FP treatment was applied at the time of seeding, and a variable rate of UAN was applied PE using the GreenSeeker^{TM} RT200 variable rate application system and our most recent N application algorithm for canola. At two of the sites (NH05 and BA06), we included a fifth treatment, Reduced N (RN), where a fertilizer N rate equivalent to the rate applied at seeding in the SF and VRA treatments was applied at the time of seeding and no further N was applied.

5.3.2 Trial Locations

In total, we conducted nine separate field-scale experiments in southeast Saskatchewan, four in 2005 and five in the 2006 growing season. The experiments NH05 and RP06 were both located near Indian Head on an Indian Head heavy clay soils. RE06 was northeast of Wolseley on an Edgeley clay loam soil. VJ05 was located near Kendal on a Weyburn light loam and VJ06 was south of Indian Head on Oxbow clay loam. The site-years referred to as BA05 and BA06 were both located south of Lemberg on mixed Oxbow loam / Yorkton loam soils. KS06 was located southeast of Balcarres, SK, just north of the Qu'Appelle Valley in the transition zone between Indian Head clay loam and Oxbow loam soils. Finally, VS05 was located just south of Raymore, SK, on an Oxbow loam soil. The specific locations of each of experimental site and other pertinent agronomic information are presented in Table 5.1.

Table 5.1. Pertinent agronomic information for various field-scale nitrogen management trials conducted in Saskatchewan during the 2005 and 2006 growing seasons.

Field ID	Location (lat long)	N-P-K-S [z] (kg ha^{-1})	Cultivar	Seed Date	Seed Rate (kg ha^{-1})	PE N App. Date	H_2O: UAN	Harvest Date
BA05	103.21, 50.62	84-28-11-17	InVigor™ 2663	05-28-05	4.5	06-Jul-05	3.3:1	09-29-05
NH05	103.65, 50.65	101-na-na-na	na	05-05-05	na	24-Jun-05	2.85:1	09-03-05
VJ05	103.66, 50.20	111-31-0-12	InVigor™ 2663	05-24-05	4.5	05-Jul-05	2.5:1	na
VS05	104.55, 51.37	123-34-0-28 [y]	InVigor™ 2663	05-11-05	na	30-Jun-05	2:1	na
BA06	103.19, 50.62	84-34-0-22[y]	InVigor™ 2663	05-21-06	4.5	1-Jul-06	1:1	09-05-06
KS06	103.62, 50.75	71-29-0-30[y]	InVigor™ 5070	05-15-06	4.5	30-Jun-06	1:1	10-05-06
RP06	103.52, 50.55	125-30-0-15	Nexera™ 830	05-11-06	5.6	27-Jun-06	0:1	09-02-06
RE06	103.16, 50.47	84-28-11-11	InVigor™ 5070	05-08-06	4.5	27-Jun-06	1:1	09-06-06
VJ06	103.58, 50.49	101-31-0-12	InVigor™ 5030	05-25-06	5.0	05-Jul-06	1:1	09-08-06

[z] Fertilizer rates are for farmer practice treatments. Unless otherwise indicated, P (P_2O_5), K (K_2O) and S rates were held constant for all N management treatments.

[y] P, K, and S rates were varied between treatments with N fertilizer rates

na – information not available

We approximated the growing season temperatures and precipitation levels for each site using the nearest Environment Canada weather station, which was located at Indian Head for all sites except for VS05, where the nearest station was located at Wynyard. While we would have preferred to measure precipitation directly at each site, we did not have the equipment to do so. Consequently, we assumed that the overall precipitation and temperature patterns at each of the sites were similar to those measured at the nearest weather station.

5.3.3 Crop Management

The fields where the experiments were located were all continuously cropped, managed using zero or minimum tillage systems, and had not been sown to canola for at least two years prior to the year of the experiment. The canola was managed using the producer's normal practices and, aside from the post-emergent N applications, the producers carried out all of the field operations. Canola at all sites except for KS06, where an airseeder equipped with 36 cm sweeps on 23 cm centers was used, was planted using low-disturbance air drills. Seeding dates ranged from May 5 to May 26 (Table 5.1). While the cultivars used varied from site to site (Table 5.1), all were herbicide tolerant and the seed was always treated with a systemic insecticide / fungicide to protect against root diseases and insect damage. Competition from pests was controlled at all site-years using registered products at the recommended crop and weed stages.

Nitrogen fertilizer rates, forms, and application methods varied from site to site depending on the producer's normal practices. Urea was the N source applied at seeding at BA05, BA06, KS06, RE06 and VS05. Urea was side-banded at BA05, BA06, and VS05 and mid-rowed banded at RE06. On the seeder used at KS06, the Vern backswept knife split the seed and placed it beneath each wing while the backswept fertilizer knife placed the fertilizer between the paired seed rows. Urea-ammonium nitrate was the N source used at seeding at NH05 and RP06 and was side-banded at both locations. At RP06, not all of the UAN applied at seeding was side-banded for all of the treatments. At this site, the 66% N rate was side-banded across the entire study area at the time of seeding and the remaining N for the FP and NR treatments was applied as surface dribble-banded UAN just prior to seeding. At VJ05, all N applied at seeding was side-banded anhydrous NH_3 for all treatments, while at VJ06 we applied 33% of the N applied in the NR treatment as surface dribble-banded UAN six days after seeding to reduce the potential for NH_3 toxicity in this treatment.

In 2005, only one NR pass, which was located in the center of each study area, was included at each site. We initially only included one NR pass in order to reduce space requirements and because the main purpose of this treatment was as a reference for determining the maximum YP of the field, not as a viable N management treatment that producers would consider. However, in 2006 we replicated the NR strip along with all of the other treatments to reduce the potential effects of spatial variability and to strengthen the statistical analysis.

Wherever possible, the producers held the rates of all non-N nutrients constant across the treatments. However, there were cases where this was not possible or was impractical and the P, K and S rates varied with the N rates. The site-years where this was the case were VS05, BA06, and KS06. While this is a known potentially confounding factor at these sites, we can only acknowledge it and assume that all non-N nutrients rates in all treatments were sufficiently high to achieve maximum grain yields. Application rates of all nutrients for the FP treatments at each site-year are reported in Table 5.1.

5.3.4 Post-Emergent N Applications

Post-emergent N was applied at all sites when the canola was between growth stages 3.1 and 4.1 (Harper and Berkenkamp 1975). The dates of the PE N applications ranged from June 24 – July 5 in 2005 and from June 27 – July 5 in 2006. The UAN used in the PE N applications was commercial grade 28-0-0. Post-emergent N was applied using a 1998 RoGator 554 (AGCO Corporation) high-clearance sprayer equipped with a Mid-Tech^{TM} RX 400p GPS receiver (Teejet^{TM} Technologies), an Accutrak automatic steering system (Accutrak Systems Ltd.), and an RT200 variable rate application system (NTech Industries) which includes six boom-mounted GreenSeeker^{TM} active optical sensors. Each of the six sensors measured canopy reflectance of visible red and NIR irradiance, calculates NDVI, and transmits the NDVI values to a controller located in the cab, which averages the individual NDVI values and conveys this information to a ruggedized PDA. The average NDVI of the six sensors was then associated with a fertilizer rate and the Raven SCS 4400 (Raven Industries Inc.) rate controller was signalled to adjust the N rate accordingly.

In both 2005 and 2006, we used liquid fertilizer nozzle assemblies that applied the UAN to the soil surface in concentrated bands. In 2005, stainless steel orifice plates were used to maintain pressure and regulate the rates along with plastic caps that directed the UAN to the soil surface in three concentrated streams. Rather than repeatedly changing orifices to achieve the application rates that we anticipated requiring, we diluted the UAN with varying amounts of water, keeping the quantities of solution applied relatively constant from one site to the next. A further advantage of diluting the UAN was that it allowed us to apply substantially lower N rates than would have otherwise been possible at our travel speeds, which in 2005 was approximately 8 km h^{-1}. In 2006, we switched to a VeriFlow 1 (SprayTarget) nozzle assembly that was capable of application rates ranging from about 35 – 347 L ha^{-1} (103 – 448 kPa) at 19 km h^{-1}. These nozzle bodies have a spring-backed orifice that allows their capacity to increase with increasing product flow and boom pressure. Because of the increased range of UAN rates and our desire to keep these experiments as practical and relevant to commercial production as possible, we increased our travel speed during the PE N applications to approximately 16 km h^{-1} in 2006. In most cases, we still diluted the UAN with water at a 1:1 ratio (by volume) in 2006 to allow lower N application rates than would have been possible with undiluted UAN. While it is debateable whether diluting the UAN with water at a 1:1 ratio is practical from a producer's perspective, this was a marked improvement from 2005, where the ratio of water to UAN ranged from 2:1 to 3.3:1. The specific dilution ratios used at each site are included in Table 5.1.

Calculating the PE N rates in the variable rate treatment was a multiple step process. The day before each PE application, we calculated the number of GDD (base temperature 0˚C) accumulated from the day after seeding to the day prior to sensing inclusive. Next, we determined the average NDVI of each NR pass using a handheld GreenSeeker^{TM} model 505 sensor mounted to a John Deere Gator (Deere and Company). We measured the NR passes for the entire length of the field, avoiding any unusual areas such as drowned out patches, drill misses / plugged seed runs, and headlands or other double-seeded areas. We then divided the NDVI of the NR treatment by the number of GDD between seeding and sensing, and used the resultant value to estimate the upper YP for the field. Depending on the level of variability from one NR pass to the next, either the overall average NDVI of all the passes or the average NDVI of the single best pass was used to determine the target yield for the field. We then calculated target N rates for the entire range of potential NDVI values. In 2005, the target N rates were saved onto a

Compact Flash card, which was read directly by the RT200 controller, and in 2006 they were manually entered into the PDA's internal memory using the 'Custom Algorithm' option in the RT200 software. There were 64 potential N rates for increasing NDVI increments of 0.016 in 2005 and 16 possible N rates for increasing NDVI increments of 0.05 in 2006. We calculated the N fertilizer rates by subtracting the estimated quantity of N removed in the grain of the crop under assessment from the estimated quantity of N removed in the grain of the high N reference crop. The N concentration of canola seed was set at 33 g N kg seed^{-1}, which corresponds to 20.6% protein. The difference in N removed from the two estimated yield potentials was then divided by an efficiency factor of 0.5 under the assumption that 50% of the applied N will potentially be lost and / or retained in soil organic matter and crop residues. We developed the empirical YP equations used in 2005 and 2006 using all of the data that was available for each year and the equations are presented in Equations 5.1 and 5.2 respectively.

$$\text{Yield}_{2005}=1408.3\times\exp[744.6\times(\text{NDVI}/\text{GDD})] \tag{5.1}$$

$$\text{Yield}_{2006}=801.5\times\exp[964.3(\text{NDVI}/\text{GDD})] \tag{5.2}$$

where GDD is the number of GDD accumulated between the day after seeding and the day prior to sensing. Equation 5.1 was calculated using Excel 2000 (MicroSoft Corporation) and equation 5.2 using SigmaPlot 2000 (Systat Software Inc.). For equation 5.1, we adjusted the best fit-curve calculated from the actual empirical data upwards by 33% under the assumption that the adjusted curve is more representative of the actual YP of the crop than the actual best-fit line (Raun, W.R. personal communication). In 2006, we decided against adjusting the empirical equation upward in the field-scale trials and evaluated both forms of the equation in small plot trials (Chapter 4). With all other factors being equal, the effect of adjusting the curves upwards is that the recommended N rates will be 33% higher than those calculated using the unadjusted curves.

5.3.5 Data Collection and Preparation

We mapped the NDVI of the canola canopy along with the N application rates using the RT200 system while applying the PE N. These were the NDVI values used in the statistical analysis. Mean NDVI values and product rates were logged once every second regardless of travel speed. Grain yield data was collected using yield monitors and the study areas were always harvested using a single machine. After harvest, each producer provided an unedited yield map of the study areas.

All initial processing of the N rate, NDVI, and grain yield data were completed using ArcGIS 9 (ESRI). The data logged during the PE UAN applications were used to locate each of the treatment passes and the combine pass closest to that of the high-clearance sprayer was selected for further analysis. The selected observations for both NDVI and yield were then assigned reference values to identify the pass, replicate, and treatment to which they corresponded. Any unusual observations were removed from both the NDVI and yield maps prior to further analysis. The first step to identifying unusual NDVI data points was to select all of the points where the NDVI was more than three standard deviations from the mean. Observing the spatial distribution of these points allowed us to easily identify any misrepresentative parts of the field such as drowned out or unseeded areas. Unusually low NDVI values did not receive any N fertilizer and were removed from the dataset and no NDVI values were considered unusually high, as all such points were presumably representative of healthy, uniform crop canopies. Any areas of the yield maps corresponding with locations where NDVI data had been removed were also removed, while observations more than three standard deviations from the mean were closely examined and removed only if thought to be inaccurate. For example, any observations where the combine speed was quickly reduced and grain yield quickly increased were immediately followed by observations with very low yields were considered unusual and removed. The coordinate system for the remaining data was then converted from decimal degrees to a Universal Transverse Mercator (UTM) coordinate system, where relative locations are expressed in meters, to facilitate spatial analyses. All further data manipulation and analysis was conducted using SAS 9.1 for Windows (SAS Institute, Inc.).

Prior to analysis, the data were averaged according their relative geographic positions using the PROC MEANS procedure of SAS 9.1 (SAS Institute, Inc.). Data were rounded and averaged every 25 m along the direction of the passes in all site-years except RP06 where, because of its large size, data were rounded and averaged every 50 m. Rounding the data according to its geographic position effectively standardized the data where measurements were not equally spaced along the length of the passes, reduced computation time, and improved model convergence for the PROC MIXED procedure that followed. For the inferential analysis that followed, we considered each rounded observation to be a distinct experimental unit and the actual number of observations for each treatment at each site-year are included in Appendix H.

5.3.6 Statistical Analyses

Data were analyzed using the PROC MIXED procedure (Littel et al. 1996) of SAS 9.1. We chose to analyze the data as a completely randomized design (CRD) with the rounded observations as experimental units for two main reasons. First, the blocks in which the treatments were assigned at seeding were physically much too large to meet the assumptions of the randomized complete block design (RCBD), with the distance from one end of a pass to the other generally exceeding the distance across all four blocs. Second, we felt that spatial variability within the passes and across the study area would make treatment differences difficult to predict if we simply used average values for each pass. The justification for assigning treatments into blocks when designing the experiments was to ensure the even distribution of the treatments across each study area. The covariance test option of the PROC MIXED procedure was used to model spatial covariance of the response variables from the residual variation. Spherical, exponential, and power covariance structures were tested for all analyses and the structure that described spatial variability of the residual error was chosen. Spatial covariance of NDVI was best described by either the exponential or spherical structures and grain yield was always best described with exponential spatial covariance structures.

All spatial analyses were conducted using either a common variance estimate or by allowing for heterogeneous variance estimates between treatments, depending which model type resulted in better model convergence. Results from the analyses allowing separate variance estimates are reported only in the cases where doing so improved the model fit criteria (-2 Residual Log Likelihood; corrected Akaike's Information Criterion), otherwise the simpler model was used (Appendix H). While the results of the spatial analyses are not presented in the main body of this chapter, covariance estimates and their associated p-values are reported in Appendix H. Treatment means were compared with one another using contrasts and differences were declared significant at $P \leq 0.05$.

5.4 RESULTS AND DISCUSSION

In 2005, mean monthly temperatures from May through August were slightly cooler than normal at both Indian Head and Wynyard (Table 5.2). While both locations received less precipitation than normal in April, initial moisture conditions were considered good at all sites. At Indian Head in 2005, precipitation levels were close to normal for May, June, and July, and well above normal in August. Wynyard received approximately normal amounts of precipitation in June, below normal precipitation in April and July, and above average rainfall in May and August. Overall, moisture conditions were generally considered adequate to excellent to good throughout the growing season at all sites in 2005.

Table 5.2. Weather information for Indian Head in 2005 and 2006 and Wynyard in 2005. Data are from Environment Canada's Online Climate Data.

	Indian Head						Wynyard			
Month	**2005**		**2006**		**Normal**^{z}		**2005**		**Normal**	
	Temp.^{y}	Precip.^{x}	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.
April	5.5	6.8	7.3	72.2	4.0	24.6	5.7	10.2	3.4	23.5
May	8.7	57.6	11.2	39.0	11.4	55.7	8.8	61.9	11.0	49.0
June	14.8	99.2	16.0	80.4	16.1	78.9	14.5	69.6	15.6	74.9
July	16.9	59.2	17.9	5.6	18.4	67.1	17.4	34.4	17.7	66.7
August	15.6	98.0	17.4	11.8	17.5	52.7	15.0	99.8	16.9	50.3
September	12.0	4.0	11.6	57.6	11.4	41.3	11.6	61.2	10.9	38.1

^{z}Climatic normals for the period from 1971 – 2000
^{y}Mean monthly temperature (degrees Celsius)
^{x}Total monthly precipitation (millimetres)

Mean monthly temperatures were considerably higher in 2006 than they were in 2005 and were closer overall to the long-term average. Conditions were initially very wet in 2006 with precipitation levels in April nearly three times higher than average. Precipitation levels at Indian Head in May and June 2006 were slightly below and approximately equal to the long-term averages respectively. From July onward, conditions at Indian Head became very dry with the last major rainfall event of the season occurring on June 24 and less than 20 mm of total precipitation in July and August.

In the following discussion, the relative mean NDVI values were used as indicators of the canola's response to N fertilizer up to the point of the PE N applications. For instance, if the treatments that had received reduced quantities of starter N had the same NDVI as the canola grown at the higher N rates, the probability of a yield response to further additions of fertilizer N was considered low (Raun et al. 2001; Raun et al. 2002; Mullen et al. 2003). In contrast, if NDVI increased with increasing rates of starter N, the probability for a yield response to PE N was considered high, with the magnitude of the response depending on the extent to which the two NDVI values differed (Raun et al. 2001; Raun et al. 2002; Mullen et al. 2003). However, bear in mind that the mean NDVI values of the NR treatments reported in Tables 5.3 through 5.11 often differed from the values used to estimate the upper YP for the field, which were determined prior to the PE N application using a handheld sensor. Because each site-year was unique and the results varied from one site-year to the next, a discussion of the results from individual sites will precede a more general discussion.

Because Tables 5.3 through 5.11 are somewhat difficult, a brief explanation of how to interpret them is provided. The mean NDVI values for each N management treatment appear in the second row from the top and the values correspond to the treatments listed directly above them. The mean N application rates and grain yields are in the second and third columns from the left and correspond to the treatments in the column on the far left. Probability levels for the effects of N management appear in the bottom four rows in the four columns furthest to the right, with p-values for treatment differences in grain yield below and to left of the diagonal line and p-values for NDVI above and to the right of the diagonal line. The p-values should be interpreted in the same manner as a correlation matrix. For example, in Table 5.3, the probability that the grain yields and NDVI values of the FP and NR treatments are not different from one another is 0.228 and 0.598 respectively.

5.4.1 BA05

At BA05, the N rates applied at seeding were 56, 84, and 125 kg N ha^{-1} for the split N, FP, and NR treatments respectively (Table 5.3). While there were no significant treatment differences in NDVI at the time of topdressing (P=0.098 – 0.753), NDVI tended to increase slightly with the N rates applied at seeding. The NDVI of the NR pass measured using the handheld sensor and used to set the upper YP in the N application algorithm was 0.820, which was considerably higher than the mean of 0.708 measured using the RT200.

Table 5.3. Least squares means and p-values determined from means comparisons of NDVI and grain yields of canola grown under different N management systems at BA05. NDVI data were analysed using a common variance estimate and yield data were analysed using separate variance estimates for each treatment. Least squares means of both NDVI and yield are adjusted for power and exponentially structured spatial covariance respectively.

Field ID	Location		Treatment^z			
BA05	103.21, 50.62		**FP**	**NR**	**SF**	**VRA**
			NDVI (SEM)			
Trtmnt^z	Total N (PE N)^y kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.701 (0.0070)	0.708 (0.007)	0.698 (0.0067)	0.689 (0.0125)
			p-values			
FP	84 (0)	2133 (38.9)		0.598	0.753	0.098
NR	125 (0)	2271 (92.1)	0.228		0.501	0.156
SF	84 (28)	2345 (65.0)	**0.034**	0.538		0.169
VRA	78 (22)	2356 (44.5)	**0.001**	0.447	0.896	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE

^{y}Total N is the sum of the quantity of N applied at seeding and that applied on July 6, 2005 (GS 3.2 – 4.1) as PE UAN. The quantity of PE N applied is enclosed in brackets.

The rates of PE N applied in the VRA treatment ranged from zero to 45 kg N ha^{-1} with a mean of 22 kg N ha^{-1} and a standard deviation of 12.3 kg N ha^{-1}. On average, the total quantity of N applied in the VRA treatment was 6 kg N ha^{-1} less than the SF and FP treatments. However, if not for the difference between mean NDVI measured with the handheld sensor and that measured with the RT200, we would have applied considerably less N in the VRA treatment.

The canola at BA05 appeared to have responded well to the PE UAN, with both the SF (P=0.034) and VRA (P=0.001) treatments yielding higher than the FP treatment. Furthermore, the grain yield of the NR treatment was not significantly different from that of either the SF (P = 0.538) or VRA (P=0.447) treatments. Because the VRA and SF treatments yielded the same as one another (P = 0.896), there was no apparent advantage to applying a variable rate of PE N relative to a fixed rate aside from the modest reduction in N use of 6 kg N ha^{-1}.

5.4.2 NH05

The fertilizer N rates applied at seeding at NH05 were 67, 101, and 151 kg N ha^{-1} for the split / reduced N, FP, and NR treatments respectively. At this site, there was strong positive relationship between the quantities of N applied at seeding and NDVI (Table 5.4). The mean NDVI of both the NR and FP treatments were significantly higher than all of the treatments where only 67 kg N ha^{-1} was applied at seeding and, while not statistically significant (P = 0.121), the mean NDVI of the NR treatment tended to be higher than that of the FP treatment.

The NDVI value used to estimate the upper yield potential for the field was 0.770, which was the same as the mean of the NR treatment determined with the RT200. Post emergent N rates in the VRA treatment ranged from 1 – 56 kg N ha^{-1} with a mean of 24 kg N ha^{-1} and a standard deviation of 11.1 kg N ha^{-1}. On average, the VRA treatment received 10 kg N ha^{-1} less fertilizer N than the SF and FP treatments.

Table 5.4. Least squares means and p-values determined from means comparisons of midseason NDVI and grain yield of canola grown under varying nitrogen management strategies at NH05. Both NDVI and yield data were analysed using separate variance estimates. Least squares means of NDVI and grain yield are adjusted for power and exponentially structured spatial covariance respectively.

Field ID	Location		Treatment^{z}				
			FP	NR	SF	VRA	RN
NH05	**103.65, 50.65**				NDVI (SEM)		
Trtmnt^{z}	Total N (PE N)^{y} kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.738 (0.0134)	0.770 (0.0104)	0.671 (0.0089)	0.674 (0.0048)	0.675 (0.0115)
					p-values		
FP	101 (0)	3132 (52.1)		0.121	**<0.001**	**<0.001**	**<0.001**
NR	151 (0)	3398 (141.3)	0.250		**0.004**	**0.009**	**0.002**
SF	101 (34)	3066 (17.5)	0.285	0.207		0.833	0.797
VRA	91 (24)	3009 (52.4)	0.141	0.153	0.363		0.898
FP	67 (0)	3001 (81.7)	0.405	0.146	0.579	0.945	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE

^{y}Total N is the sum of the total quantity of N applied at seeding and that applied on June 24, 2005 (GS 3.2 – 4.1) as PE UAN. The quantities of PE N applied are enclosed in brackets.

At NH05, there were no significant differences in yield observed between the treatments, despite having quite a high range of 397 kg ha^{-1}. While the NR treatment yielded considerably higher than the others, this treatment had a relatively high error term, at least in part because of the reduced number of observations and weak spatial covariance estimates in this treatment and thus, was not significantly different from any of the other treatments. Other than this, the differences in mean canola yields were always within 131 kg N ha^{-1} of one another, although the yield of the FP treatment tended to be higher than the split-N treatments.

5.4.3 VJ05

At VJ05, the N rates applied at seeding were 74, 112 and 168 kg N ha^{-1} for the split N, FP, and NR treatments respectively (Table 5.5). Compared to the adjacent passes, plant populations were visibly reduced in the NR treatment, presumably a result of NH_3 toxicity. Nitrogen fertilizer at this site was side-banded anhydrous NH_3 and the soil was a relatively coarse textured Weyburn loam. Furthermore, conditions at seeding were very wet, which possibly reduced the separation between the seed and fertilizer, thus the potential for NH_3 toxicity was high, especially at the higher N rates. Consequently, the mean NDVI of the NR treatment was significantly lower than that of the FP (P<0.001) and VRA treatments (P<0.001), but not the SF treatment (P=0.382). The NDVI of the VRA treatment was significantly higher than that of any other treatments including the SF treatment (P < 0.001), although each had received the same rates of fertilizer N at seeding.

Table 5.5. Least squares means and p-values determined from means comparisons of midseason NDVI and grain yield of canola grown under varying nitrogen management strategies at VJ05. NDVI data were analysed using a common variance estimate and yield data were analysed using separate variance estimates. Least squares means of both variables are adjusted for exponentially structured spatial covariance.

Field ID	Location			Treatment		
VJ05	**103.66, 50.20**		FP	NR	SF	VRA
				NDVI		
Trtmnt^{z}	Total N (PE N)^{z} kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.749 (0.0040)	0.727 (0.0062)	0.732 (0.0040)	0.761 (0.0041)
				p-values		
FP	112 (0)	2355 (37.4)		**<0.001**	**<0.001**	**0.005**
NR	168 (0)	2257 (27.1)	**0.048**		0.382	**<0.001**
SF	112 (38)	2297 (60.0)	0.433	0.558		**<0.001**
VRA	79 (5)	2126 (100.1)	0.147	0.325	0.237	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE

^{y}Total N is the sum of the total quantity of N applied at seeding and that applied on July 5, 2005 (GS 3.1 – 3.3) as PE UAN. The quantity of PE N applied is enclosed in brackets.

The NDVI value used to set up the N application algorithm for the VRA treatment was 0.740, which was slightly higher than the mean NDVI of 0.727 measured using the RT200. Only 5 kg N ha^{-1} on average was applied PE in the VRA treatment with a range of zero to 22 kg N ha^{-1}, which resulted in an average reduction in total fertilizer N use of 33 kg N ha^{-1} relative to the FP and SF treatments. It is conceivable that with such low N rates recommended, producers would be better off deciding not to apply PE N and avoiding the fixed costs of applying PE N.

Canola seed yields at VJ05 ranged from 2126 – 2355 kg ha^{-1} and the overall mean yield was 2259 kg ha^{-1}. The only significant difference in grain yields was between the FP treatment and the NR treatment (P = 0.048), whereby the FP treatment yielded 98 kg ha^{-1} higher than the NR treatment. Although the FP treatment appeared to outyield the VRA treatment by more than 200 kg ha^{-1}, the standard error of the VRA treatment was relatively high and the difference was not significant (P = 0.147). Still, the difference is worth noting because if real, such a reduction in grain yield would certainly be important from a producer's perspective and would more than the cover the cost of the added N. It is also worth noting that the Type III test of fixed effects in the Mixed model was not significant (Table H.8; P=0.229) for grain yield at this site-year, thus when all of the treatments were considered, there were no significant differences. The contrasts reported in Table 5.5 are still valid as they are direct comparisons of one treatment to the next.

5.4.4 VS05

The rates of N applied at seeding at VS05 were 82, 123, and 184 kg N ha^{-1} for the split N, FP, and NR treatments respectively (Table 5.6). At this site-year, the mean NDVI of neither the NR nor the FP treatments were significantly different from those of the treatment that received reduced rates of N at seeding, indicating minimal potential for a response to PE N. While the NR treatment tended to have the highest NDVI, we could not necessarily attribute this to differences in response to N, as the SF treatment tended to have a higher NDVI than the FP treatment and the FP and VRA treatments were similar. Based on the information available, the difference in NDVI between the SF and VRA treatments can only be attributed to spatial variability as both of these treatments had received the same rates of N fertilizer at the time of sensing.

Table 5.6. Least squares means and p-values determined from means comparisons of midseason NDVI and grain yield of canola grown under varying nitrogen management strategies at VS05. NDVI data were analyzed using separate variance estimates and yield data using common variance estimates. Least squares means of both response variables are adjusted for exponentially structured spatial covariance.

				Treatment^z		
Field ID	Location		FP	NR	SF	VRA
VS05	**104.55, 51.37**			NDVI (SEM)		
Trtmnt^z	Total N (PE N)^y kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.772 (0.0204)	0.818 (0.012)	0.798 (0.0084)	0.773 (0.0075)
				------------------- p-values --------------------		
FP	123 (0)	1697 (69.6)		0.149	0.342	0.985
NR	184 (0)	1905 (100.0)	**0.014**		0.279	0.077
SF	123 (41)	1993 (72.4)	**<0.001**	0.227		**0.034**
VRA	95 (14)	1849 (67.6)	**<0.001**	0.524	**0.003**	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE
^{y}Total N is the sum of the total quantity of N applied at seeding and that applied on June 30, 2005 (GS 3.2 – 4.1) as PE UAN. The quantities of PE N applied are enclosed in brackets.

The mean NDVI of the NR pass that was used to set the upper YP for the field was 0.830, which was comparable to the mean NDVI of 0.818 measured using the RT200. Post-emergent N rates in the VRA treatment at VS05 ranged from zero to 50 kg N ha^{-1} with a mean of 14 kg N ha^{-1}. On average, this resulted in a savings of 27 kg N ha^{-1} in total N use relative to the FP and SF treatments.

While the NR treatment yielded similarly to the split N treatments (P=0.227 – 0.554), at 1697 kg ha^{-1}, the FP treatment yielded unusually lower than the other treatments. However, the SF treatment yielded 144 kg ha^{-1} higher than the VRA treatment (P=0.003), possibly an indication that the N rates recommended by the N application algorithm were not sufficient to maximize grain yields. However, that the SF treatment had a higher NDVI than the VRA treatment and that neither of these treatments yielded different from the NR treatment suggests that spatial variability was a more probable cause of the difference between the VRA and SF treatments.

5.4.5 BA06

At BA06, the N rates applied at seeding were 54, 84, and 113 kg N ha^{-1} for the split / reduced N, FP, and NR treatments respectively (Table 5.7). At the time of top-dressing, the NDVI values of all the treatments that received a reduced N rate at seeding were significantly lower than the mean NDVI values of both the NR and FP treatments (P<0.001). Overall, the NDVI measurements at this site indicated that while 54 kg N ha^{-1} was probably not enough to maximize yield, a yield response to N rates beyond 113 kg ha^{-1} was unlikely.

We used the mean NDVI of the best NR pass, which was 0.714, to estimate the upper YP at BA06, while the overall mean NDVI of the NR treatment measured with the RT200 was 0.658. The N rates applied in the VRA treatment ranged from zero to 44 kg N ha^{-1}, with a mean of 22 kg N ha^{-1} and standard deviation of 9.7 kg N ha^{-1}. At 8 kg N ha^{-1}, the average fertilizer N savings in the VRA treatment relative to the FP and SF treatments were modest.

The canola at BA06 yielded well overall, ranging from 1866 kg ha^{-1} for the VRA treatment to 2153 kg ha^{-1} at the highest N rate. As anticipated from the NDVI measurements, the yields of the FP and NR treatments were not significantly different from one another (P=0.261). While the NR treatment yielded higher than the SF (P=0.053), VRA (P=0.024), and RN (P=0.012) treatments, none of these three treatments yielded differently than the FP treatment (P=0.102 – 0.388). There was, however, no observed yield response to the PE N, as both the SF (P=0.344) and VRA (P=0.990) treatments yielded the same as the RN treatment.

Table 5.7. Least squares means and p-values determined from means comparisons for midseason NDVI values and grain yields of canola grown under varying nitrogen management systems at BA06. NDVI data were analyzed using a common variance estimate and grain yield data using separate variance estimates and are adjusted for exponentially structured spatial covariance.

Field ID	Location				Treatment[z]		
BA06	**103.19, 50.62**		FP	NR	SF NDVI (SEM)	VRA	RN
Treatment[z]	Total N (PE N)[y] kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.659 (0.0064)	0.658 (0.0064)	0.629 (0.0061)	0.631 (0.0063)	0.628 (0.0063)
			------------------- p-values -------------------				
FP	84 (0)	2032 (71.5)		0.860	**<0.001**	**<0.001**	**<0.001**
NR	113 (0)	2153 (73.6)	0.261		**<0.001**	**<0.001**	**<0.001**
SF	84 (30)	1950 (57.7)	0.388	**0.053**		0.983	0.813
VRA	76 (22)	1866 (79.0)	0.147	**0.024**	0.411		0.819
RN	54 (0)	1868 (60.4)	0.102	**0.012**	0.344	0.990	

[z] FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE

[y] Total N is the sum of the total quantity of N applied at seeding and that applied on July 1, 2006 (GS 3.2 – 4.1) as PE UAN. The quantities of PE N applied are enclosed in brackets.

5.4.6 KS06

At KS06, the fertilizer N rates applied at seeding were 48, 70, and 122 kg N ha^{-1} for the split N, FP, and NR treatments respectively (Table 5.8). At the time of top-dressing, none of the NDVI values measured using the RT200 were significantly different from one another, although there was a tendency for the treatments that received higher rates of N at seeding to have higher mean NDVI values. In addition, while the difference was not significant, the NDVI of the NR treatment tended to be considerably higher than that of any of the other treatments, including the FP treatment.

Table 5.8. Least squares means and p-values determined from means comparisons for midseason NDVI and grain yields of canola grown under varying nitrogen management systems at KS06. Both NDVI and yield data were analysed using separate variance estimates. Least squares means of both variables are adjusted for exponentially structured spatial covariance.

Field ID	Location		Treatment^z			
			FP	NR	SF	VRA
KS06	**103.62, 50.75**		NDVI (SEM)			
Trtmnt^z	Total N (PE N)^y kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.718 (0.0044)	0.740 (0.0042)	0.704 (0.0044)	0.710 (0.0043)
			------------------- p-values --------------------			
FP	70 (0)	1944 (49.0)		0.215	0.252	0.301
NR	122 (0)	2111 (36.0)	**0.016**		0.112	0.090
SF	70 (22)	2009 (56.1)	0.392	0.146		0.721
VRA	80 (32)	1932 (64.2)	0.888	**0.033**	0.380	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE
^{y}Total N is the sum of the total quantity of N applied at seeding and that applied on June 30, 2006 (GS 3.1 – 3.3) as PE UAN. The quantities of PE N applied are enclosed in brackets.

We used the mean NDVI of the best NR pass, which was 0.839, to determine the upper yield potential for the VRA treatment at KS06. The PE N rates applied in the VRA treatment at this site-year ranged from 17 – 46 kg N ha^{-1} with a mean of 32 kg N ha^{-1}, thus the total N rate in this treatment was 10 kg N ha^{-1} higher than the FP and SF treatments. As with several of the other site-years, fertilizer N requirements in the VRA treatment may have been overestimated because of the large difference between the NDVI value used to set the upper yield potential and that reported in Table 5.8.

Nonetheless, the recommended rates did not appear to be unreasonable considering that the NDVI of the NR treatment tended to be substantially higher than for the FP treatment.

The overall mean grain yield at KS06 was 1999 kg ha^{-1} with the VRA treatment yielding the lowest at 1932 kg ha^{-1} and the NR treatment yielding the highest at 2111 kg ha^{-1}. Except for the NR treatment yielding 167 kg ha^{-1} higher the FP treatment ($P=0.016$) and 179 kg ha^{-1} higher than the VRA treatment ($P=0.033$), no other treatment differences were significant. Furthermore, there was no apparent advantage to applying a variable rate of PE N compared with a fixed rate, especially considering that we applied more N in the VRA treatment.

5.4.7 RE06

The N rates applied at seeding at RE06 were 55, 84, and 126 kg N ha^{-1} for the split N, FP, and the NR treatments respectively (Table 5.9). At this site, the NDVI values of both the SF and VRA treatments were significantly lower than the NDVI of the NR and FP treatments ($P<0.001$), indicating a strong probability for a response to N rates beyond 55 kg N ha^{-1}. The NDVI of the NR treatment tended to be higher than that of the FP treatment; however the difference was not statistically significant ($P=0.085$).

We used the mean NDVI of the best NR pass, which was 0.784, to determine the target YP for the VRA treatment, which again was substantially higher than the overall treatment mean of 0.665 measured with the RT200. The PE N rates applied in the VRA treatment ranged from 15 – 50 kg N ha^{-1} and the overall mean was 30 kg N ha^{-1}; thus the mean total N rate applied in the VRA treatment was 2 kg N ha^{-1} higher than the SF and FP treatments.

Grain yields of all of the N management treatments were high at RE06 with an overall mean of 2847 kg ha^{-1} and no significant differences among the treatments. As signified by the observed NDVI values, the NR treatment did not yield significantly higher than the FP treatment (P=0.700). Furthermore, there was no apparent advantage to variable rate applications relative to applying the fixed rate of N, which actually yielded 100 kg ha higher than the VRA treatment (P=0.068). Nor was there any yield advantage to applying N fertilizer in a split application system relative to applying everything at seeding (P=0.112) and splitting the N application increased the overall costs and labour requirements.

Table 5.9. Least squares means and p-values determined from means comparisons for midseason NDVI values and grain yields of canola grown under varying nitrogen management systems at RE06. Both NDVI and yield data were analysed using common variance estimates and are adjusted for power and exponentially structured spatial covariance respectively.

Field ID	Location		Treatment^{z}			
			FP	NR	SF	VRA
RE06	**103.16, 50.47**			NDVI (SEM)		
Trtmnt^{z}	Total N (PE N)^{y} kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.656 (0.0094)	0.665 (0.0093)	0.637 (0.0097)	0.637 (0.0096)
				p-values		
FP	84 (0)	2818 (57.0)		0.091	**<0.001**	**<0.001**
NR	126 (0)	2839 (57.0)	0.700		**<0.001**	**<0.001**
SF	84 (29)	2916 (58.8)	0.112	0.209		0.961
VRA	86 (31)	2816 (57.9)	0.954	0.692	0.068	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE
^{y}Total N is the sum of the total quantity of N applied at seeding and that applied on June 27, 2006 (GS 3.2 – 4.1) as PE UAN. The quantities of PE N applied are enclosed in brackets.

5.4.8 RP06

The N rates applied at seeding at RP06 were 95, 143, and 213 kg N ha^{-1} for the split N, FP, and NR treatments respectively (Table 5.10). At the time of topdressing, there was a strong tendency for the mean NDVI values observed to increased with increasing N fertilizer rates, despite the fact that the rates applied at this site-year were relatively high. The NDVI of the NR treatment was significantly higher than that of all of the other treatments ($P < 0.001$), while that of the FP treatment was higher than both the SF and VRA treatments ($P < 0.001$). The observed NDVI values of the SF and VRA treatments were very similar to one another ($P = 0.453$).

Table 5.10. Least squares means and p-values determined from means comparisons for midseason NDVI values and grain yields of canola grown under varying nitrogen management systems at RP06. NDVI data were analysed using a common variance estimate and yield data were analysed using separate variance estimates. Both are adjusted for exponentially structured spatial covariance.

Field ID	Location		Treatment^z			
RP06	**103.52, 50.55**		FP	NR	SF	VRA
			NDVI			
Trtmnt^z	Total N (PE N)^y kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.675 (0.0040)	0.686 (0.0041)	0.660 (0.0041)	0.662 (0.0041)
			------------------- p-values -------------------			
FP	143 (0)	2106 (36.7)		**<0.001**	**<0.001**	**<0.001**
NR	213 (0)	2186 (13.5)	0.066		**<0.001**	**<0.001**
SF	143 (48)	2001 (84.2)	0.344	0.157		0.453
VRA	121 (26)	2080 (48.4)	0.673	0.074	0.473	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding (used to estimate potential crop response to N fertilizer); SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE

^{y}Total N is the sum of the total quantity of N applied at seeding and that applied on June 27, 2006 (GS 3.1 – 3.2) as PE UAN. The quantities of PE N applied are enclosed in brackets.

We used the NDVI of the best NR pass, which was 0.760, to calculate the PE N rates for the VRA treatment. Once again, this value was considerably higher than the overall treatment mean of 0.686 measured using the RT200, thus we may have overestimated the recommended rates in the VRA treatment. The PE N rates applied in the VRA ranged from zero to 36 kg N ha^{-1} and had a mean of 25 kg N ha^{-1} which resulted in 22 kg N ha^{-1} less N being applied than in the SF and FP treatments.

The grain yields of the various treatments at RP06 were very similar to one another, ranging from 2001 kg ha^{-1} in the SF treatment to 2186 kg ha^{-1} in the NR treatment. Furthermore, there were no significant differences in grain yield among the treatments, although the NR treatment tended to yield higher than the others (P=0.066 – 0.157). While there was no yield advantage to applying a variable rate of PE N relative to fixed rate (P=0.473), less fertilizer N was used in the VRA treatment, thus the efficiency of the applied N was increased with the variable rate.

5.4.9 VJ06

The N rates applied at seeding at VJ06 were 67, 100, and 150 kg N ha^{-1} for the split N, FP, and NR treatments respectively (Table 5.11). At the time of topdressing, the mean NDVI values of all treatments were similar, suggesting that there was a low probability for a response to N rates exceeding 67 kg ha^{-1}.

Table 5.11. Least squares means and p-values determined from means comparisons of midseason NDVI and grain yield of canola grown under varying nitrogen management strategies at VJ06. NDVI data were analyzed using a common variance estimate and grain yield data using separate variance estimates for each treatment and are adjusted for exponentially structured spatial covariance.

Field ID	Location		Treatment^{z}			
			FP	NR	SF	VRA
VJ06	**103.58, 50.49**		NDVI (SEM)			
Trtmnt^{z}	Total N (PE N)^{y} kg N ha^{-1}	Yield (SEM) kg ha^{-1}	0.611 (0.0052)	0.609 (0.0052)	0.611 (0.0051)	0.614 (0.0053)
			------------------- p-values -------------------			
FP	100 (0)	2276 (29.4)		0.478	0.942	0.484
NR	150 (0)	2197 (19.6)	**0.036**		0.544	0.227
SF	100 (33)	2229 (50.3)	0.447	0.568		0.412
VRA	107 (40)	2333 (55.5)	0.393	0.070	0.200	

^{z}FP – Farmer Practice: All N applied at time of seeding; NR – Nitrogen Rich: Elevated rate of N applied at seeding; SF – Split Application / Fixed Rate: Reduced quantity of N applied at seeding and remainder applied PE; VRA – Variable Rate Application: Reduced quantity of N applied at seeding and variable rate, determined using sensor-based estimates of yield potential and potential response to N, applied PE

^{y}Total N is the sum of the total quantity of N applied at seeding and that applied on July 5, 2006 (GS 3.1 – 3.3) as PE UAN. The quantities of PE N applied are enclosed in brackets.

We used the overall average NDVI of the four NR passes, which was 0.751, to estimate the upper yield potential of the study area. This value was much higher than the value of 0.611 measured using the RT200; thus again we may have applied more PE UAN at VJ06 than necessary. The PE N rates applied in the VRA treatment ranged from 20 – 63 kg N ha^{-1} with an overall mean of 40 kg N ha^{-1}. In total, the average N rate in the VRA treatment was 7 kg ha^{-1} higher than for the SF and FP treatments.

While the VRA treatment appeared to have highest mean yield at VJ06, it did not yield significantly different from any of the other treatments (P=0.070 – 0.393). However, the FP treatment at VJ06 was significantly higher than the NR treatment (P=0.036). Aside from this somewhat unexpected result, no other significant differences in grain yield among the treatments were significant. We could not attribute the low yield of the NR treatment to NH_3 toxicity in 2006 because we applied 33% of the N in this treatment as surface dribble-banded UAN, thus the same rate of N was side-banded at seeding as in the FP treatment. Again, there was no advantage to applying a variable rate compared with applying a fixed rate of PE N as slightly more N was applied in the VRA treatment with no yield benefit.

5.4.10 Summary of results

While our results varied from one site-year to the next, they allow us to draw several general conclusions. The main criteria used to evaluate the performance of the VRA treatment were marginal grain yields, marginal N fertilizer use, marginal yields divided by marginal N fertilizer use, and marginal profitability. To simplify the discussion, the VRA treatment was primarily compared to the benchmark practice of applying the entire, fixed quantity of N at seeding, which was represented by the FP treatment. While we could not calculate NUE in these trials as a criterion for evaluating the VRA treatment, we can reasonably infer that NUE was increased in the VRA treatment in the specific studies where grain yield was not negatively impacted and N fertilizer use was reduced (Fageria and Baligar 2005).

Overall, our results indicated that NDVI measured with the RT200 variable rate application system was generally capable of detecting differences in crop growth that presumably resulted from varying levels of N fertility. At 44% of the site-years, the mean NDVI of the NR treatment was significantly higher than that of the split / reduced N treatments and tended to be higher at 78% of the sites. Similarly, the mean NDVI of the FP treatment was significantly higher than that of the treatments where a reduced rate of N was applied at seeding in 40% of the possible cases (Table 5.12). Except for VJ05 and VS05, where the NDVI values of the NR and FP treatments were lower than those of the split N treatments, NDVI always tended to increase with the quantity of N applied at seeding. This is consistent with Behrens et al. (2004), who measured the NDVI of oilseed rape canopies at growth stages 3.1 and 4.1 (Harker and Berkenkamp 1975) and found that fertilizer N consistently increased NDVI at both growth stages. In winter wheat at Feekes 5, Mullen et al. (2003) found that in all but 2 out of 23 instances, the NDVI values of fertilized plots were greater than in the unfertilized plots.

Using our canola N application algorithm to determine PE N rates resulted in an overall reduction in fertilizer N use at 67% of the site-years (Table 5.12). In the remaining three site-years, we applied 2 – 10 kg N ha^{-1} more fertilizer N in the VRA treatment than in the SF and FP treatments. Notice that all of the experiments where we applied more fertilizer N in the VRA treatment than in the FP treatment were completed in 2006. It is our opinion that the environmental conditions in 2006 resulted in a worst-case scenario for managing N using optical sensors. Although soil moisture was abundant at the time of application for all of the sites, no significant precipitation events occurred after June 24 and the conditions that followed were hot and dry through harvest. This likely resulted in increased volatilization (Stumpe and Monen 1986; Whitehead and Raistrick 1991) and reduced mobility of the PE UAN, and an overall reduction in canola YP (Schjoerring et al 1995; Brandt and McGregor 1997).

Table 5.12. Marginal grain yields, marginal N rates, and marginal yields divided by the marginal N rates for each site-year. Values are used to compare the VRA treatment directly with the FP treatment

Site-Year	NDVI[z]	Yield[y]	N Rate[x]	Yield / N Rate[w]	Profit[v]
		kg canola ha^{-1}	kg N ha^{-1}		\$ ha^{-1}
BA05	(-0.012)	+223**	-6	37.2 (+)	75
NH05	(-0.064)**	(-123)	-10	12.3[u]	(-51)
VJ05	0.012**	(-229)	-33	6.9[u]	(-68)
VS05	0.001	+146**	-28	5.2 (+)	68
BA06	(-0.028)**	(-166)	-8	20.8[u]	(-69)
KS06	(-0.014)	(-12)	+10	1.2 (-)	(-30)
RE06	(-0.019)**	(-2)	+2	1.0 (-)	(-18)
RP06	(-0.013)**	(-26)	-22	1.2[u]	(-3)
VJ06	(-0.003)	(+82)	+7	11.7[t]	9

*significant at $0.01p\leq 0.05$; **significant at $p\leq 0.01$

[z] NDVI of the FP treatment subtracted from that of the VRA treatment

[y] Yield of the FP treatment subtracted from that of the VRA treatment

[x] Total quantity of N applied in the FP treatment subtracted from that applied in the VRA treatment

[w] Ratio of the marginal yield to the marginal N rate. Not considering the cost of the PE N application, values followed by (+) indicate that the VRA treatment is economically viable while values followed by (-) indicate that the VRA treatment is not economically viable, regardless of the market values of the two commodities.

[v] Marginal profit of the VRA treatment relative to the FP treatment (VRA – FP) assuming \$0.375 kg canola, \$1.00 kg N, and a \$15.00 ha^{-1} cost of application for the VRA treatment only.

[u] Not considering the cost of the PE N application, the VRA treatment would be economically viable provided that the ratio of the price of N fertilizer to the price received for canola exceeds this ratio.

[t] Not considering the cost of the PE N application, the VRA treatment would be economically viable if the ratio of the price of N fertilizer to the price received for canola does not exceed this ratio.

In terms of grain yield, there were only two site-years, BA05 and VS05, where the yields of the FP and VRA treatments were significantly different from one another and in both cases the VRA treatment yielded higher than the FP treatment (Table 5.12). While there were instances where the yields of the VRA treatment were low enough relative to the FP treatment to be of concern to producers, these differences were never statistically significant. Such was the case at NH05, VJ05, and BA06, where the VRA treatment yielded 123, 229, and 166 kg ha^{-1} less than the FP treatment respectively, which would have likely have been sufficient to pay for any additional N inputs, especially when the cost of application is considered. For the remaining five site-years, grain yields of the FP and VRA treatments were always within 100 kg ha^{-1} of each other.

While no previous literature that evaluated the RT200 variable rate application system was found and these sensors have not previously been used with canola, comparable studies with cereals in the southern United States and Mexico have been published. Compared with applying fixed rates of N, Raun et al. (2002) either maintained or increased grain yields using a fixed rate of pre-plant N along with a sensor-based variable rate in-crop application. In the Yaqui Valley near Sonora, Mexico, determining and applying fixed rates of PE N based on NDVI measurements and N rich reference crops resulted in a 30% reduction in N use with no effect on grain yield (Ortiz-Monasterio and Raun 2007). In comparison, the rates of the VRA treatments in the current study ranged from 29% lower than the FP treatment at VJ05 to 14% greater at KS06.

While we usually reduced N fertilizer consumption in the VRA treatment without compromising grain yield, the VRA treatment was rarely more profitable than the FP treatment, and in the majority of cases was slightly less profitable (Table 5.12). We assumed that producers receive \$0.375 kg canola^{-1}, pay \$1.00 kg fertilizer N^{-1} and that the combined cost of the PE N application and sensing technology cost was \$15.00 ha^{-1}.

Revenues were calculated using actual grain yields, regardless of whether or not the yields of the two treatments were significantly different from one another. Note that in all three cases where the VRA treatment was more profitable than the FP treatment, the VRA treatment yielded higher than the FP treatment. Likewise, at NH05, VJ05, and BA06, where the VRA treatment was considerably less profitable than the FP treatment, mean canola yields in the VRA treatment tended to be relatively low compared to the FP treatments. The ratios presented in the second last column of Table 5.12 are the ratio of the price of N fertilizer to the price received for canola that must be exceeded for the VRA treatments where both N use and grain yield were reduced to be profitable. In the case of VJ06, where both N use and yield in the VRA treatment were higher than in the FP treatment, the ratio of the price of N fertilizer to the price received for canola must not exceed this ratio. With our assumptions used to calculate the marginal returns, this ratio was 2.67, in which case VJ06 and RP06 were the only site-years (of those where economic viability depended on the relative prices of grain and fertilizer) where the VRA treatment would potentially be viable under the assumed economic conditions. However, bear in mind that this does not take into account the added cost of the PE N application, which is reflected in the results of the marginal economic analysis in the last column of Table 5.12.

The results of the economic analyses in the current study were less favourable for the VRA applications than in the comparable studies. For irrigated spring wheat in the Yaqui Valley in Mexico, Ortiz-Monasterio and Raun (2007) reported increases in economic margins of \$62 ha^{-1} using a sensor-based N management system, likely at least in part because they were able to use irrigation to move the PE N into the soil and ensure adequate water availability after the PE N application. For winter wheat in Oklahoma, Raun et al. (2002) reported comparatively modest increases in economic margins of $13 ha^{-1} for sensor-based N management relative to applying a fixed rate of N prior to seeding. One key difference between the economic analysis presented in these studies and our own is that the authors did not include an additional application cost when calculating revenues for the treatments where they applied PE N. While this may be justifiable for winter cereals where applying fertilizer in the spring is a common practice or in less developed parts of the world where seeding equipment is not configured for single pass seeding / fertilizer applications, the fixed costs of PE N applications cannot reasonably be excluded for production of spring crops in western Canadian.

5.5 CONCLUSIONS

While managing N fertilizer in canola production using split applications of N and an optical sensor-based N fertilizer application algorithm appears to be feasible, there was not generally an economic advantage to doing so. For producers who do not traditionally apply PE N, committing to doing so over a large number of acres can be a formidable constraint to the adoption of this technology. There are good reasons for such hesitation, including potential conflicts with herbicide and fungicide applications as well as the risk of wet conditions preventing timely PE N applications. However, for producers who already routinely apply PE N, the transition to using active optical sensors such as the GreenSeeker^{TM} should be comparatively easy and this technology has potential to help producers to make better-informed, more objective decisions regarding PE N than has been previously possible.

The discrepancies between the NDVI values measured by the handheld sensor and those determined using the six sensors of the RT200 system are also a concern. It is possible that these differences may have weakened the performance of the VRA treatment in this study, because the values determined using the handheld sensor were consistently higher values than those determined with the RT200, thus reducing the potential savings in N fertilizer. With the six sensors, it was not uncommon for one or more of the sensors to be centered over weak rows or otherwise sparsely vegetated areas such as sprayer tire tracks. While we tried to avoid such areas with the handheld sensor, they commonly brought down the mean NDVI measured with the RT200. Using a reference NDVI value that is too high to set up the algorithm results in applying consistently higher PE N rates and applying N in areas of the field where it normally would not have been called for. The simplest way to prevent this is to determine the NDVI of the N Rich reference using the RT200 rather than a handheld unit. While there were definite logistic advantages to setting up the fields using the handheld sensor during this project, it is very easy to use the RT200 to do so when using the algorithms that are included with the RT200 software. At the time of writing, the N application algorithm for canola algorithm developed in this study is available with the latest version of the RT200 software, thus taking the initial NDVI measurements using the RT200 will be relatively easy in commercial applications.

The fact that we increased revenues using optical sensors only when the yield of the VRA treatment was higher than the FP treatment may be an indication that the approach to using these sensors to fine-tune N rates needs revision. Rather than trying to reduce N rates up front, it might be more profitable for producers to apply rates of N at seeding that are sufficient to produce average yields and reserve PE N applications for situations where there is potential to increase grain yields sufficiently to cover the cost of the PE N application. Such an approach would still require establishing a non-N limiting reference and an assessment of the crop during the growing season, but would effectively reduce the number of acres for which PE N is required and reduce the overall added application costs. As mentioned earlier, committing to PE N over a large number of acres is not an appealing option for most producers in western Canada and may be one of the greatest potential deterrents to the commercial adoption of this technology.

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6.0 OVERALL SYNTHESIS

The overall objective of this study was to determine whether the GreenSeeker^{TM} optical sensor and established methods of using it can be used to improve our ability to match N application rates with canola (*Brassica napus* L.) N requirements and potentially increase N fertilizer use-efficiency. To achieve this, we first had to establish that normalized difference vegetation index (NDVI) measurements could be utilized to estimate the yield potential (YP) of canola during the growing season, which is an essential component to estimating post-emergent (PE) N requirements (Raun et al. 2002). Because NDVI increases over the course of the growing season (Behrens et al. 2002; Martin et al. 2007), we tested five potential divisors to normalize NDVI for differences in growth rate in which measurements worked best.

The second component to this study involved evaluating the feasibility of PE N applications in canola using non-N limiting reference crops and sensor-based estimates of YP as a basis for determining PE N requirements. If it is feasible, the final question is whether using optical sensors as an N management tool will provide sufficient benefit for producers to justify adopting the technology. Potential benefits could arise by maintaining grain yields with less total fertilizer N, or by increasing grain yields with PE N when there is opportunity to do so (Raun et al. 2002).

In order to generate the empirical data required to establish the relationships between NDVI and canola yield over the growing season, we established a two-year study with canola in 2005 at Brandon, Indian Head, Ottawa, Scott, and Swift Current, where the treatments were a factorial combination of six N fertilizer rates and four seeding rates. Varying N and seed rates established plots with a wide range of yield potentials and early season variability in aboveground biomass. Overall, the NDVI of canola canopies increased through the vegetative growth stages, levelled off in the early reproductive stages (late bolting) and decreased to a certain extent after this point. This is essentially the same pattern of temporal variation in NDVI as described for corn and is a result of increased N uptake and biomass production early in the season, saturation of NDVI with increasingly dense canopies in the late vegetative / early reproductive stages, and plant senescence late in the growing season (Freeman et al. 2007; Martin et al. 2007).

The exponential relationships between grain yield and NDVI for individual site-years and sensing-dates were generally very weak or non-existent prior to the five-leaf stage of canola. The weak relationships observed early on were likely at least partly due to the high variability in plant populations, which presumably affected NDVI early in the growing season (Warren and Metternicht 2005) more than it affected grain yields (Rood and Major 1984; Angadi et al. 2003). Canola adapts to low plant populations through increased vegetative growth and branching (Rood and Major 1984; Angadi et al. 2003), thus the effects of seeding rate on the relationship between NDVI and yield decreased as the crop developed. The relationship between NDVI and yield improved as the crops progressed through the vegetative growth stages until peaking at some point between mid-bolting and 5% flowering (GS 3.2 – 4.1; Harper and Berkenkamp 1975), and generally became weak when the canola went into full bloom. Basnyat et al. (2004) suggested that canola's highly reflective flowers and leaf loss during flowering negatively affect the relationship between NDVI and grain yield during this growth stage. However, we purposely developed the equation using data from a wide-range of plant populations because canola seedling establishment tends to be variable between and within individual fields (Warren and Metternicht 2005) and we wanted our YP equations to apply over a range of plant densities.

When we compiled all of the NDVI data collected between growth stages 2.5 and 4.1 from all of the sites-years except Scott in 2005, where the plots were severely damaged by hail, there was a positive relationship between NDVI and canola yield (R^2 = 0.340). Dividing NDVI by days from planting or various heat units did not consistently improve the correlation with grain yield (R^2 = 0.331 – 0.423). Visual inspection of the plotted data revealed that the NDVI data from Scott and Swift Current in 2006 did not display the same relationship with canola yield as the other sites, especially when divided by growing degree days calculated using base temperatures of 0˚ C (GDD_0) and 5˚ C (GDD_5) and corn heat units (CHU). It appeared that while dividing NDVI by heat units decreased variability in the measurements collected from individual site-years, it increased the separation between the data from Scott and Swift Current in 2006 and the remaining site-years. It is probable that the hot, dry conditions that occurred late in the season in 2006 reduced grain yields at these sites (Angadi et al. 2000; Morrison and Stewart 2002), with the negative effects occurring after sensing. However, dividing NDVI by physiological days (P-days) in the first analysis was more effective than using any of the other divisors (R^2=0.423), and P-days were the only unit that noticeably improved the relationship relative to NDVI on its own. It would appear that the relatively low optimum and maximum temperatures of 17˚ C and 30˚ C better accounted for the reduced crop growth that occurs during extremely hot periods than any of the other divisors did.

Previous research has suggested that when extreme post-sensing conditions occur after sensing and adversely affect grain yields, the data should not be used to develop empirical relationships for estimating YP from NDVI (Raun et al. 2001; Raun et al. 2005). Consequently, we removed the data from these two site-years to see if the relationships would improve. When data from both years at Scott and 2006 at Swift Current were excluded, the coefficients of determination for the NDVI-yield increased from 0.340 to 0.444 and dividing NDVI by the number of days between planting and sensing increased the R^2 to 0.474. Dividing NDVI by each of the heat units that were tested further strengthened the relationship with grain yield and the strongest correlation was observed when NDVI was divided by CHU (R^2=0.562). Similar results were observed when corn heat units was substituted with growing degree-days, regardless of the base temperature used (R^2=0.545 – 0.552). While dividing NDVI by physiological days provided the best fit in the first combined analysis, it did not perform as well as the other heat units when Scott and Swift Current 2006 were excluded (R^2=0.528). As such, we would probably not recommend P-days as the standardizing unit of choice, primarily because of the complexity of the calculations and their inconsistent performance relative to the other units. While days from planting did not work as well as the heat units for normalizing NDVI, it was still an improvement over NDVI on its own and therefore a viable alternative to heat units in cases where temperature data is not available.

Having established that it is possible to estimate canola YP using NDVI measurements collected between the five-leaf stage and early flowering, our objective was to determine whether it was possible to use these estimates to fine-tune N fertilizer rates in canola production. To achieve this, we completed a series of field experiments with canola both in small plots and on a commercial scale.

The principal N management treatments in these experiments were: 1) Farmer Practice (FP) where all fertilizer N was placed in-soil at seeding at rates considered sufficient to produce average yields, 2) Nitrogen Rich (NR) where all fertilizer N was applied in-soil at seeding at rates considered sufficient to ensure that N would not become limited during the growing season, 3) Split application / Fixed rate (SF) where N rates that were approximately 66% of those applied in the FP treatment were placed in the soil at the time of seeding and the remaining 34% was applied PE as surface dribble-banded urea ammonium nitrate (UAN), and 4) a variable rate (VRA) treatment where the same rate of N was applied at seeding as in the SF treatment, and PE N rates were determined using in-season NDVI measurements and high N reference plots. In the plot studies, we included a check where no fertilizer N was applied. To determine if there was a response to PE N we included a reduced N (RN) treatment where the same rate of starter N was applied as in the split N treatments and no additional PE N was applied in some of the plot and on-farm trials,.

In the plot experiments, which were located at Indian Head and Scott, we decreased total N fertilizer use in the VRA treatments by 20 – 56 kg N ha^{-1} relative to the FP and SF treatments. Despite the reduction in N fertilizer use, grain yields in the VRA and FP treatments were only different from one-another at Indian Head in 2006, where it was extremely dry late in the growing season. Previous work completed at Indian Head and Scott showed that when no N is applied at seeding, surface applications of PE N are not an effective method of providing N to crops under drought conditions (Holzapfel et al. 2007). Surface applications of PE N require precipitation to move the fertilizer into the soil to allow access by the crops (Holzapfel et al. 2007) and precipitation shortly after application can greatly decrease the potential for volatile losses (Whitehead and Raistrick 1991). However, at three out four site-years grain yields in the VRA treatment were significantly lower than for the NR treatment indicating that we did not maximize grain yields in the VRA treatment. The exception was Scott in 2006 where the two treatments yielded the same.

Agronomic N use-efficiency (ANUE) was highly variable, ranging from as low as 2.8 kg grain kg N applied^{-1} to 14.7 kg kg^{-1}. Nitrogen management significantly affected ANUE in both years at Indian Head but not at Scott and the trend at all site-years was for ANUE to be lowest in the NR treatment. At Indian Head, ANUE was higher in the VRA treatment than the FP treatment in 2005, but the two treatments had similar ANUE in 2006. However, the observed ANUE in the FP treatment at Indian Head in 2006 was achieved with higher N rates and grain yields than the ANUE observed for the VRA treatment. Overall, our results are consistent with previous research, which has shown ANUE to increase with increasing grain yields and decrease with increasing N rates, especially when N rates exceed crop demands (Smith et al. 1988; Hocking et al. 2002).

The results of the on-farm trials were similar in many respects to those of the plot experiments, although we could not calculate ANUE for lack of an unfertilized check. In the on-farm trials, the mean total N rates applied in the VRA treatment ranged from 33 kg N ha^{-1} lower to 10 kg ha^{-1} higher than in the FP treatment. Despite the differences in applied N rates, the yields of VRA and FP treatments only differed from one another in two cases, in both of which where the yield of the VRA treatment was higher than that of the FP treatment. While there were no cases where we observed a yield advantage to the VRA treatment relative to the SF treatment, the application rates were frequently lower in the VRA treatment. Furthermore, we did not significantly increase yields with PE N at either of the two site-years where an RN treatment was included.

For these trials, we completed a simple economic analysis where we assumed that the price received for canola was \$0.375 kg canola^{-1}, the price paid for N fertilizer was \$1.00 kg N^{-1}, and the PE N application / technology cost was \$15.00 ha^{-1}. Under these assumptions, the fertilizer savings in the VRA treatment were rarely sufficient to cover the fixed costs of applying PE N. In each of the three cases where the economic returns in the VRA treatment were higher than for the FP treatment, the VRA treatment yielded higher than the FP treatment. In comparison, Ortiz-Monasterio and Raun (2007) reported increases in net economic margins of \$62 ha^{-1} from irrigated spring wheat using sensor-based N management practices. Using similar methods for winter wheat, Raun et al. (2002) reported comparatively modest increases in economic margins of \$13 ha^{-1}. One important difference between these studies and our own is that neither Ortiz-Monasterio and Raun (2007) nor Raun et al. (2002) included the additional cost of the PE N application when calculating marginal economic returns. While excluding this cost may be justified in systems where the crop's entire N fertilizer requirements are not typically applied during the seeding operation, such as for winter cereals or perhaps in less developed countries where seeding equipment is not configured to do so, this is not typically the case for no-till, spring-seeded crops in western Canada.

Overall, the results of these trials indicated that while both canola YP and relative N status are estimable using NDVI measurements, it is uncertain whether doing so will result in increased NUE or net economic returns over the long-term relative to more conventional N fertilization practices. Except in crop production systems where PE is already routinely applied and it can be justified not to consider this application an additional cost, this technology is more likely to increase NUE than economic returns. The reason for this is that in cases where fertilizer use is reduced and grain yields are not affected, the reductions in N use must be sufficiently large to cover the fixed costs of applying PE N for an economic benefit to be realized. On the other hand, any reductions in N fertilizer use without a subsequent reduction in grain yields should result in increased efficiency of the applied N. However, in cases where increases in grain yield result from the PE N applications, relative increases in both NUE and economic returns are much more likely.

There are good reasons why producers may be hesitant to adopt this technology and increase their reliance on PE N. Perhaps the greatest deterrent to adoption is the increased costs associated with applying PE N over a large number of acres. Applying PE in a timely manner can potentially interfere with applications of herbicides and fungicides, and wet conditions potentially could outright prevent applying PE N early enough to attain a grain yield response. Our results show that canola yield potential can be most accurately estimated during the bolting stages and previous research has shown that PE N must be applied prior to flowering to prevent yield losses from occurring (Lafond et al. 2007). This leaves a relatively narrow window over which we can estimate YP and response to N and apply the N early enough to reasonably expect a yield response. Furthermore, as observed in the plot studies at Indian Head in 2006 and in previous work completed at Indian Head and Scott, dry conditions late in the growing season can decrease the efficacy of PE N and result in substantial yield penalties (Holzapfel et al. 2007).

One potential way in which we may be able to utilize optical sensing in N management of canola while reducing the number of acres that require PE N along with the risks associated with PE N applications in dry years is to alter our overall approach to managing N using these sensors. Instead of reducing the quantity of N applied at seeding, it may be more profitable and less risky to apply enough N at seeding to produce average yields and use the sensors to identify situations where PE N will allow producers to capitalize on opportunities for increased grain yields. Such an approach would still necessitate establishing an N rich reference in every field to estimate whether a response to PE N is likely; however reducing N rates applied at seeding less aggressively would reduce the number of instances where PE N is required. Regardless of how much N is applied at seeding, if no differences in NDVI are observed between the NR reference and the adjacent crop, no further action is required and the added cost of the PE N is eliminated. In cases where the NDVI of the NR reference is higher than that of the adjacent crop, producers should quantify the potential increases in grain yield and only proceed to apply PE N when the magnitude of the increase in yield is sufficiently large to cover the cost of the PE application under realistic economic assumptions.

It is worth recognizing that the empirical equation we proposed for estimating canola YP could have potential applications extending beyond determining PE N requirements. An objective means of estimating YP during the growing season could be a valuable decision making tool for producers who are forward marketing grain, deciding whether to invest in additional crop inputs such as fungicides or insecticides, or allocating storage for the incoming crop. Other agricultural sectors that could potentially benefit from a fast, objective tool for estimating YP include grain buyers and marketing groups as well as crop insurance providers.

A potential weakness of the YP equations that should be acknowledged is that they were mostly generated using NDVI measurements from a single cultivar, InVigor™ 5020 and under no-till conditions. Behrens et al. (2004) showed that differences between cultivars affect the absolute NDVI of canola canopies, whereby the NDVI of unfertilized plots for some cultivars was lower than that of the fertilized plots for others. However, Behrens et al. (2004) did not specifically look at the relationship between NDVI and grain yields across the varieties, thus it is possible that these cultivars differed similarly in grain yields. We speculate that the wide range of environments and the varying seed rates used in our own study may have reduced the overall importance of cultivar. However, characteristics such as leaf size and orientation that sometimes differ between cultivars could conceivably conflict with the ability of our equations to estimate canola YP from one cultivar to the next. Either way, an in depth evaluation looking at the relationships between NDVI and grain yield for multiple varieties would better enable us to comment on the suitability of using these equations to estimate canola YP independently of varieties. In terms of the affects of no-till versus conventional tillage systems, while other research as shown that soil properties and crop residues can affect NDVI (Nagler et al. 2000), it is likely that the canola canopy will be sufficiently dense at the time of sensing that tillage system will not affect the performance of the equations.

With respect to the N application algorithms used in this study, there is also the issue regarding our assumption that the upper yield potential of the canola would be same across the entire field if N were not limiting. Furthermore, the algorithm assumed that applying PE N could completely correct any apparent N deficiencies that were detected. In the case of highly variable landscapes or in fields with non-uniform plant populations, these assumptions will almost certainly not be met because of factors such as variability in plant density (Angadi et al. 2003) or soil moisture (Pennock et al. 2001). Nonetheless, the algorithms used in this study should work well in reasonably level fields with reasonably uniform plant populations. As suggested earlier, the methods described by Raun et al. (2005) would likely be better suited for estimating crop response to PE N when the landscape or crop establishment is variable. Raun et al. (2005) used a response index calculated by dividing the mean NDVI of the high N pass by the mean NDVI of the adjacent pass to estimate the average response to PE N across the range of potential estimated yield potentials. Thus, if the response index is 1.25, the assumption is that yields can be increased by 25% with PE N, regardless of the crop's current YP. Raun et al. (2005) suggest estimating the maximum YP for the field using the smaller of the YP estimated using the highest NDVI value observed in the field or an arbitrary maximum biological YP for the crop. Thus, we would recommend that the an application algorithm utilizing Raun et al.'s (2005) methods for canola determining N requirements be made available, especially for use in fields with highly variable landscapes or plant populations. Completing further research evaluating Raun et al.'s (2005) methods against those used in the current study over various types of terrain would enhance our overall understanding of how optical sensors should be used to estimate PE N requirements.

In addition, we need to develop a more thorough understanding of the potential environmental and economic benefits of using this technology to fine-tune PE N rates in canola relative to the current benchmark practices. Because of temporal and spatial variability in environmental conditions, we cannot reasonably expect the same potential benefits to sensor-based N management each year. Gaining a better understanding of the long-term benefits that might be expected from managing N using sensors requires that studies carried out over a considerably longer period than two years. As indicated earlier, such an investigation should ideally encompass different approaches to using the sensors and quantify the potential risks and benefits of the different approaches across different ecozones. It is conceivable that the best approach to managing N using optical sensors at Indian Head, SK or Selkirk, MB may not be the same as it would be in drier regions such as Swift Current, SK or Lethbridge, AB.

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7.0 APPENDICES

APPENDIX A – SUMMARY TABLES FOR RESPONSE VARIABLES MEASURED IN CANOLA NITROGEN RATE BY SEEDING RATE STUDIES PRESENTED IN CHAPTER 3

Table A.1. Mean plant densities (plants m^{-2}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Ottawa 2005.

	OTTAWA 2005						
Nitrogen Rate kg N ha^{-1}	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
	25	50	100	200	lin.	quad.	cub.
				plants m^{-2}			
0	26	50	68.1	103	**	ns	ns
25	29	40	62	126	**	ns	ns
50	22	43	60	108	**	ns	ns
100	26	53	106	98	**	**	ns
150	26	61	48	131	**	ns	*
200	18	46	101	123	**	**	ns
Orthogonal Contrasts							
lin.	ns	ns	ns	ns			
quad.	ns	ns	ns	ns			
cub.	ns	ns	ns	ns			

ns – not significant at $p \leq 0.005$
*sigrificant at $0.01 \leq p \leq 0.05$
** sigrificant at $p \leq 0.01$

Table A.2. Mean plant densities (plants m^{-2}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Swift Current 2006.

	SWIFT CURRENT 2006						
Nitrogen Rate kg N ha^{-1}	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
	25	50	100	200	lin.	quad.	cub.
				plants m^{-2}			
0	15	44	89	139	**	*	ns
25	17	51	90	102	**	**	ns
50	16	40	66	98	**	ns	ns
100	16	30	53	74	**	ns	ns
150	8	25	41	50	**	ns	ns
200	7	18	27	51	**	ns	ns
Orthogonal Contrasts							
lin.	ns	**	**	**			
quad.	ns	ns	ns	**			
cub.	ns	ns	ns	ns			

ns – not significant at $p \leq 0.005$
*sigrificant at $0.01 \leq p \leq 0.05$
** sigrificant at $p \leq 0.01$

Table A.3. Mean seed yields (kg ha^{-1}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Swift Current 2005.

SWIFT CURRENT 2005							
	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
Nitrogen Rate kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
				kg ha^{-1}			
0	349	363	332	311	ns	ns	ns
25	1001	1023	1022	909	ns	ns	ns
50	1234	1455	1334	1324	ns	ns	ns
100	1548	1655	1541	1994	**	ns	ns
150	1321	1648	1556	2132	**	ns	ns
200	1325	1513	1622	1719	*	ns	ns
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	**	**	**	**			
cub.	*	*	**	ns			

ns – not significant at p≤0.005

*sigrificant at 0.01≤p≤0.05

** sigrificant at p≤0.01

Table A.4 Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on canola biomass yield (kg ha^{-1}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate					kg ha^{-1}					
0 kg N ha^{-1}	n/a	1637	2485d	2177c	n/a	n/a	3347d	1074b	n/a	n/a
25 kg N ha^{-1}	n/a	1683	3679c	3097bc	n/a	n/a	4549c	1651a	n/a	n/a
50 kg N ha^{-1}	n/a	1723	4497bc	3961ab	n/a	n/a	5208bc	1738a	n/a	n/a
100 kg N ha^{-1}	n/a	1701	4955ab	4357ab	n/a	n/a	6459a	1753a	n/a	n/a
150 kg N ha^{-1}	n/a	1441	4404bc	4594a	n/a	n/a	6206ab	1843a	n/a	n/a
200 kg N ha^{-1}	n/a	1723	5601a	3939ab	n/a	n/a	6042ab	1671a	n/a	n/a
Seed Rate										
25 seeds m^{-2}	n/a	1385b	4653	3934	n/a	n/a	n/a	1141c	n/a	n/a
50 seeds m^{-2}	n/a	1563b	4215	3858	n/a	n/a	n/a	1494b	n/a	n/a
100 seeds m^{-2}	n/a	1652b	4255	3766	n/a	n/a	n/a	1829a	n/a	n/a
200 seeds m^{-2}	n/a	2038a	3957	3192	n/a	n/a	n/a	2023a	n/a	n/a
ANOVA ***Source***					p – values					
N-Rate	n/a	ns	**	**	n/a	n/a	**	**	n/a	n/a
Seed-Rate	n/a	**	ns	ns	n/a	n/a	n/a	**	n/a	n/a
N*Seed	n/a	ns	ns	ns	n/a	n/a	n/a	ns	n/a	n/a
Replicate	n/a	**	ns	ns	n/a	n/a	ns	ns	n/a	n/a
Res. C.V.	n/a	25.2	23.7	36.3	n/a	n/a	21.7	29.8	n/a	n/a
Contrast										
N-Lin.	n/a	ns	**	**	n/a	n/a	**	**	n/a	n/a
N-Quad.	n/a	ns	**	**	n/a	n/a	**	**	n/a	n/a
N-Cub.	n/a	ns	**	ns	n/a	n/a	ns	ns	n/a	n/a
Seed-Lin.	n/a	**	*	*	n/a	n/a	n/a	**	n/a	n/a
Seed-Quad	n/a	ns	ns	ns	n/a	n/a	n/a	**	n/a	n/a
Seed-Cub.	n/a	ns	ns	ns	n/a	n/a	n/a	ns	n/a	n/a

n/a – data not available for this site-year; ns – F-test not significant ($p \le 0.05$); * significant at $0.01 \le p \le 0.05$; ** significant at $p \le 0.01$

Table A.5. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on N content of canola biomass (g N kg biomass^{-1}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate	g N kg^{-1}									
0 kg N ha^{-1}	n/a	n/a	22.2c	24.8cd	n/a	n/a	15.5c	31.3d	n/a	n/a
25 kg N ha^{-1}	n/a	n/a	23.2c	23.4d	n/a	n/a	15.4c	35.4c	n/a	n/a
50 kg N ha^{-1}	n/a	n/a	22.8c	26.3c	n/a	n/a	15.8c	38.5bc	n/a	n/a
100 kg N ha^{-1}	n/a	n/a	29.9b	34.3b	n/a	n/a	18.9b	41.1ab	n/a	n/a
150 kg N ha^{-1}	n/a	n/a	33.0a	36.6a	n/a	n/a	20.6ab	43.4a	n/a	n/a
200 kg N ha^{-1}	n/a	n/a	34.3a	38.4a	n/a	n/a	21.7a	43.4a	n/a	n/a
Seed Rate										
25 seeds m^{-2}	n/a	n/a	29.5a	34.5a	n/a	n/a	n/a	40.9a	n/a	n/a
50 seeds m^{-2}	n/a	n/a	28.7a	32.7b	n/a	n/a	n/a	41.3a	n/a	n/a
100 seeds m^{-2}	n/a	n/a	26.7b	27.9c	n/a	n/a	n/a	37.4b	n/a	n/a
200 seeds m^{-2}	n/a	n/a	25.3b	27.4c	n/a	n/a	n/a	35.8b	n/a	n/a
ANOVA ***Source***	p – values									
N-Rate	n/a	n/a	**	**	n/a	n/a	**	**	n/a	n/a
Seed-Rate	n/a	n/a	**	**	n/a	n/a	n/a	**	n/a	n/a
N*Seed	n/a	n/a	*	*	n/a	n/a	n/a	ns	n/a	n/a
Replicate	n/a	n/a	ns	*	n/a	n/a	**	*	n/a	n/a
Res. C.V.	n/a	n/a	7.9	6.9	n/a	n/a	11.3	9.8	n/a	n/a
Contrast										
N-Lin.	n/a	n/a	**	**	n/a	n/a	**	**	n/a	n/a
N-Quad.	n/a	n/a	ns	**	n/a	n/a	ns	**	n/a	n/a
N-Cub.	n/a	n/a	**	**	n/a	n/a	*	ns	n/a	n/a
Seed-Lin.	n/a	n/a	**	**	n/a	n/a	n/a	**	n/a	n/a
Seed-Quad	n/a	n/a	ns	**	n/a	n/a	n/a	ns	n/a	n/a
Seed-Cub.	n/a	n/a	ns	ns	n/a	n/a	n/a	ns	n/a	n/a

n/a – data not available for this site-year; ns – F-test not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p \leq 0.01$

Table A.6. Mean whole plant N content (g N kg biomass^{-1}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Indian Head 2005.

	INDIAN HEAD 2005						
Nitrogen Rate kg N ha^{-1}	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
	25	50	100	200	lin.	quad.	cub.
	g N kg biomass^{-1}						
0	23.5	23.1	22.2	19.9	*	ns	ns
25	22.5	26.3	21.8	22.3	ns	ns	**
50	23.8	23.0	22.2	22.4	ns	ns	ns
100	34.5	30.9	29.0	25.2	**	ns	ns
150	36.2	33.9	31.4	30.5	**	ns	ns
200	36.6	35.1	33.8	31.7	**	ns	ns
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	*	ns	ns	ns			
cub.	**	*	*	ns			

ns – not significant at p≤0.005
*sigrificant at 0.01≤p≤0.05
** sigrificant at p≤0.01

Table A.7. Mean whole plant N content (g N kg biomass^{-1}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Indian Head 2006.

	INDIAN HEAD 2006						
Nitrogen Rate kg N ha^{-1}	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
	25	50	100	200	lin.	quad.	cub.
	g N kg biomass^{-1}						
0	27.6	27.0	21.8	22.1	**	*	ns
25	29.2	24.5	21.2	18.9	**	**	ns
50	31.0	28.6	21.5	24.2	**	**	ns
100	39.6	35.7	32.5	29.2	**	*	ns
150	40.6	39.2	33.1	33.3	**	**	ns
200	39.2	41.2	37.5	35.6	**	ns	ns
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	**	ns	ns	ns			
cub.	*	**	*	*			

ns – not significant at p≤0.005
*sigrificant at 0.01≤p≤0.05
** sigrificant at p≤0.01

Table A.8. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on mid-season N uptake (kg N ha^{-1}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate					kg N ha^{-1}					
0 kg N ha^{-1}	n/a	n/a	55.1d	54.5c	n/a		52.4c	28.4b	n/a	n/a
25 kg N ha^{-1}	n/a	n/a	85.2c	72.4bc	n/a		70.3bc	29.6b	n/a	n/a
50 kg N ha^{-1}	n/a	n/a	103.5c	106.0b	n/a		83.0b	32.0b	n/a	n/a
100 kg N ha^{-1}	n/a	n/a	147.5b	147.6a	n/a		121.5a	42.0a	n/a	n/a
150 kg N ha^{-1}	n/a	n/a	145.3b	151.2a	n/a		127.1a	42.3a	n/a	n/a
200 kg N ha^{-1}	n/a	n/a	190.6a	165.2a	n/a		131.9a	45.0a	n/a	n/a
Seed Rate										
25 seeds m^{-2}	n/a	n/a	139.8a	139.6a	n/a		n/a	34.9b	n/a	n/a
50 seeds m^{-2}	n/a	n/a	124.3ab	127.2ab	n/a		n/a	35.3b	n/a	n/a
100 seeds m^{-2}	n/a	n/a	117.6bc	109.5bc	n/a		n/a	35.8ab	n/a	n/a
200 seeds m^{-2}	n/a	n/a	103.1c	89.8c	n/a		n/a	40.2a	n/a	n/a
ANOVA ***Source***					p – values					
N-Rate	n/a	n/a	**	**	n/a		**	**	n/a	n/a
Seed-Rate	n/a	n/a	**	**	n/a		n/a	*	n/a	n/a
N*Seed	n/a	n/a	ns	ns	n/a		n/a	ns	n/a	n/a
Replicate	n/a	n/a	ns	ns	n/a		ns	**	n/a	n/a
Res. C.V.	n/a	n/a	23.7	36.8	n/a		25.1	19.1	n/a	n/a
Contrast										
N-Lin.	n/a	n/a	**	**	n/a		**	**	n/a	n/a
N-Quad.	n/a	n/a	ns	**	n/a		**	**	n/a	n/a
N-Cub.	n/a	n/a	*	ns	n/a		ns	ns	n/a	n/a
Seed-Lin.	n/a	n/a	**	**	n/a		n/a	**	n/a	n/a
Seed-Quad	n/a	n/a	ns	ns	n/a		n/a	*	n/a	n/a
Seed-Cub.	n/a	n/a	ns	ns	n/a		n/a	ns	n/a	n/a

n/a – data not available for this site-year; ns – F-test not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p \leq 0.01$

Table A.9. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on grain N content (g N kg grain^{-1}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate					g N kg^{-1}					
0 kg N ha^{-1}	29.6d	na	27.6c	28.4c	34.3b	na	39.6c	31.5c	24.8d	30.1d
25 kg N ha^{-1}	30.7d	na	28.9c	29.3c	34.2b	na	39.3c	30.9c	22.8e	34.9c
50 kg N ha^{-1}	31.4cd	na	27.5c	30.1c	34.8ab	na	39.3c	31.8c	24.2d	39.0b
100 kg N ha^{-1}	33.1bc	na	31.5b	32.2b	35.2ab	na	40.5b	33.7b	29.1c	44.4a
150 kg N ha^{-1}	35.1ab	na	32.9b	34.4a	36.3a	na	41.3a	36.3a	34.5b	45.0a
200 kg N ha^{-1}	36.1a	na	35.6a	35.8a	36.3a	na	41.8a	37.1a	37.4a	45.1a
Seed Rate										
25 seeds m^{-2}	33.7a	na	31.1ab	31.7	35.9	na	n/a	34.5a	29.4	40.3ab
50 seeds m^{-2}	33.4a	na	31.7a	32.1	35.2	na	n/a	33.7ab	28.6	40.6a
100 seeds m^{-2}	31.5b	na	29.4b	31.3	34.8	na	n/a	32.8b	28.8	39.3bc
200 seeds m^{-2}	32.1ab	na	30.3ab	31.7	34.9	na	n/a	33.2ab	28.4	38.9c
ANOVA ***Source***					p – values					
N-Rate	**	na	**	**	**	na	**	**	**	**
Seed-Rate	**	na	*	ns	ns	na	n/a	*	ns	**
N*Seed	ns	na	ns	ns	ns	na	n/a	ns	ns	**
Replicate	ns	na	**	**	ns	na	ns	**	**	**
Res. C.V.	7.3	na	8.3	6.4	5.6	na	2.0	6.3	5.1	4.3
Contrast										
N-Lin.	**	na	**	**	**	na	**	**	**	**
N-Quad.	ns	na	ns	ns	ns	na	ns	ns	**	**
N-Cub.	ns	na	ns	ns	ns	na	**	*	**	ns
Seed-Lin.	*	na	ns	ns	ns	na	n/a	ns	ns	**
Seed-Quad	*	na	ns	ns	ns	na	n/a	*	ns	ns
Seed-Cub.	ns	na	ns	ns	ns	na	n/a	ns	ns	ns

n/a – data not available for this site-year; ns – F-test not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p \leq 0.01$

Table A.10. Mean grain N content (g N kg grain^{-1}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Swift Current 2006.

	SWIFT CURRENT 2006						
	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
Nitrogen Rate kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
	g N kg grain^{-1}						
0	32.2	30.0	29.9	28.4	**	ns	ns
25	37.4	36.3	34.4	31.7	**	ns	ns
50	40.8	40.0	38.7	36.3	**	ns	ns
100	43.8	45.6	44.4	43.9	ns	ns	ns
150	44.4	45.4	44.7	46.1	ns	ns	ns
200	43.2	46.3	45.1	45.6	ns	ns	*
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	**	**	**	**			
cub.	ns	*	ns	ns			

ns – not significant at p≤0.005
*sigrificant at 0.01≤p≤0.05
** sigrificant at p≤0.01

Table A.11. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on the quantity of N removed in the canola seed (kg N ha^{-1}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate					kg N ha^{-1}					
0 kg N ha^{-1}	33.1c	na	51.3d	41.2e	101.5b	na	53.9d	28.4b	8.4e	10.5d
25 kg N ha^{-1}	53.3b	na	69.7c	48.5d	106.3b	na	62.3cd	29.6b	22.6d	17.9c
50 kg N ha^{-1}	54.1b	na	70.0c	60.5c	117.8b	na	66.0c	32.0b	32.2c	23.4ab
100 kg N ha^{-1}	68.2a	na	89.8b	77.8b	118.0b	na	81.8b	42.0a	48.5b	26.0a
150 kg N ha^{-1}	75.5a	na	96.4ab	88.7a	119.8b	na	89.7b	42.3a	56.9a	22.5ab
200 kg N ha^{-1}	78.8a	na	105.3a	94.0a	140.9a	na	98.7a	45.0a	57.9a	19.8bc
Seed Rate										
25 seeds m^{-2}	50.9b	na	71.6c	63.1b	103.8b	na	n/a	35.0b	34.3	13.1d
50 seeds m^{-2}	60.4ab	na	89.4a	67.8ab	117.9a	na	n/a	35.3b	37.9ab	34.6c
100 seeds m^{-2}	66.0a	na	77.3bc	72.5a	123.3a	na	n/a	35.8ab	36.9ab	61.3b
200 seeds m^{-2}	64.8a	na	83.3ab	70.5a	123.8a	na	n/a	40.2a	41.6a	85.2a
ANOVA ***Source***					p – values					
N-Rate	**	na	**	**	**	na	**	**	**	**
Seed-Rate	**	na	**	**	**	na	n/a	*	**	**
N*Seed	ns	na	ns	ns	ns	na	n/a	ns	*	**
Replicate	ns	na	ns	ns	ns	na	ns	**	*	**
Res. C.V.	25.3	na	18.4	10.4	17.1	na	13.7	19.1	18.3	20.5
Contrast										
N-Lin.	**	na	**	**	**	na	**	**	**	**
N-Quad.	**	na	*	**	ns	na	ns	ns	**	**
N-Cub.	ns	na	ns	ns	ns	na	ns	ns	ns	**
Seed-Lin.	**	na	ns	**	**	na	n/a	ns	**	**
Seed-Quad	*	na	ns	**	*	na	n/a	**	ns	**
Seed-Cub.	ns	na	**	ns	ns	na	n/a	ns	ns	**

n/a – data not available for this site-year; ns – F-test not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p \leq 0.01$

Table A.12. Mean quantities of N removed in the seed (kg N ha^{-1}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Swift Current 2005.

SWIFT CURRENT 2005							
	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
Nitrogen Rate kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
			kg N ha^{-1}				
0	8.5	8.7	8.1	8.2	ns	ns	ns
25	22.9	23.6	23.2	20.6	ns	ns	ns
50	30.6	35.0	32.5	30.7	ns	ns	ns
100	46.1	47.0	44.9	55.9	*	ns	ns
150	47.5	56.1	52.9	71.0	**	ns	ns
200	50.0	56.7	59.9	63.6	*	ns	ns
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	**	**	**	**			
cub.	ns	ns	ns	*			

ns – not significant at $p \leq 0.005$
*sigrificant at $0.01 \leq p \leq 0.05$
** sigrificant at $p \leq 0.01$

Table A.13. Mean quantities of N removed in the seed (kg N ha^{-1}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Swift Current 2006.

SWIFT CURRENT 2006							
	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
Nitrogen Rate kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
			kg N ha^{-1}				
0	8.2	9.7	11.8	12.2	ns	ns	ns
25	13.0	17.0	21.1	20.4	*	*	ns
50	15.4	23.1	25.9	29.4	**	ns	ns
100	17.1	26.7	24.2	33.6	**	ns	**
150	14.6	18.0	29.0	28.6	**	*	ns
200	10.2	19.7	17.0	32.4	**	ns	**
Orthogonal Contrasts							
lin.	ns	*	*	**			
quad.	**	**	**	**			
cub.	ns	**	ns	**			

ns – not significant at $p \leq 0.005$
*sigrificant at $0.01 \leq p \leq 0.05$
** sigrificant at $p \leq 0.01$

Table A.14. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on agronomic nitrogen use-efficiency (kg grain kg N applied^{-1}).

	Brandon		Indian Head		Ottawa		Scott		Swift Current	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
N Rate					kg grain kg N applied^{-1}					
25 kg N ha^{-1}	24.3a	0.1	22.0a	9.0	6.1	12.4a	8.8a	2.7	26.0a	6.9a
50 kg N ha^{-1}	12.3ab	0.3	13.9ab	11.7	8.3	4.9b	6.4a	2.4	20.0b	5.2a
100 kg N ha^{-1}	9.4b	-0.7	10.0b	9.9	3.8	4.8b	6.6a	3.5	13.4c	2.4b
150 kg N ha^{-1}	7.0b	0.1	7.3b	7.7	2.3	4.0b	5.4a	1.8	8.8d	1.0bc
200 kg N ha^{-1}	5.4b	-0.1	5.6b	6.0	4.6	3.0b	5.0a	1.6	6.0d	0.4c
Seed Rate										
25 seeds m^{-2}	8.6	-1.1	10.6	10.7ab	5.0	4.5	n/a	3.3	13.4	1.6c
50 seeds m^{-2}	12.0	-0.2	12.5	7.1bc	7.7	4.1	n/a	1.0	15.1	2.9bc
100 seeds m^{-2}	11.8	-0.3	11.6	12.2a	2.6	6.6	n/a	2.4	14.9	3.6ab
200 seeds m^{-2}	14.3	1.2	12.4	5.5c	4.8	8.1	n/a	3.0	16.0	4.5a
ANOVA ***Source***						p – values				
N-Rate	**	ns	**	ns	ns	**	ns	ns	**	**
Seed-Rate	ns	ns	ns	**	ns	ns	n/a	ns	ns	**
N*Seed	ns	ns	ns	ns	ns	ns	n/a	ns	ns	ns
Replicate	ns	*	ns	*	ns	ns	ns	*	ns	ns
Res. C.V.	120.8	-5875	104.6	61.6	261.2	112.3	123.8	227.4	26.0	65.6
Contrast										
N-Lin.	**	ns	**	*	ns	**	ns	ns	**	**
N-Quad.	ns	ns	ns	ns	ns	ns	ns	ns	**	**
N-Cub.	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Seed-Lin.	ns	ns	ns	*	ns	ns	n/a	ns	ns	**
Seed-Quad	ns	ns	ns	ns	ns	ns	n/a	ns	ns	ns
Seed-Cub.	ns	ns	ns	**	ns	ns	n/a	ns	ns	ns

n/a – data not available for this site-year; ns – F-test not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p \leq 0.01$

Table A.15. Mean fall residual soil NO_3-N levels following canola grown under varying levels of N fertilizer and results of ANOVA and contrasts describing the effects of N fertilizer rate on fall residual soil NO_3-N.

	Indian Head 2005	Scott 2006	Indian Head 2006		
	0 – 60 cm			60 – 120cm	0 – 120cm
N Rate	kg NO_3-N ha^{-1}				
0 kg N ha^{-1}	26.0c	15.8b	9.4	6.2	15.6
25 kg N ha^{-1}	31.4bc	15.1b	10.7	6.2	16.9
50 kg N ha^{-1}	25.5c	14.9b	22.8	16.1	38.9
100 kg N ha^{-1}	33.0bc	15.4b	13.1	6.8	19.9
150 kg N ha^{-1}	39.8b	19.5b	18.1	20.3	38.4
200 kg N ha^{-1}	58.3a	44.8a	54.9	17.1	72.0
	p-values				
Source					
N rate	**	**	ns	ns	ns
Replicate	ns	**	ns	ns	ns
Res. CV	34.8	93.4	94.0	81.0	82.3
Contrast					
Linear	**	**	**	ns	*
Quadratic	**	**	ns	ns	ns
Cubic	ns	ns	ns	ns	ns

ns –not significant ($p \leq 0.05$); * significant at $0.01 \leq p \leq 0.05$; ** significant at $p \leq 0.01$

APPENDIX B – DATES, GROWTH STAGES, DAYS FROM PLANTING AND ACCUMULATED HEAT UNITS FOR NDVI MEASUREMENTS OF CANOLA PLOTS AT VARIOUS LOCATIONS IN NITROGEN RATE BY SEEDING RATE STUDY PRESENTED IN CHAPTER 3

Table B.1. Dates of NDVI measurement and the associated crop stages (Harper and Berkenkamp 1975), days from planting, and heat units for canola plots at Brandon, MB.

			DFP^y	GDD$_0$^{x}	GDD$_5$^{w}	CHU^v	P-Days^u
Year	Date	Crop Stage^z	days	°C			
2005	June 3	1 – 2.1	16	232.2	152.2	248.9	105.9
	June 7	2.2	20	296.4	196.4	325.0	137.2
	June 14	2.3	27	398.4	263.4	435.5	188.8
	June 21	2.4	34	538.4	368.4	604.5	232.4
	June 28	3.2	41	661.3	456.3	746.3	279.2
	June30	3.3	43	692.5	477.5	783.3	295.8
	July5	4.2	48	793.0	539.0	887.2	331.1
	July 13	5.1	56	975.0	681.0	1105.5	374.5
2006	June 13	2.1 – 2.2	33	477.8	312.8	495.3	208.7
	June 16	2.3	36	532.9	352.8	559.4	227.3
	June 19	2.4	39	593.3	398.3	632.1	245.7
	June 23	3.2	43	662.4	447.4	713.0	273.6
	June 26	3.3	46	713.9	483.9	773.8	294.9
	July 6	4.2	56	903.6	623.6	993.2	356.4
	July 10	4.3	60	987.2	687.2	1087.9	379.7

^{z}Harker and Berkenkamp 1975; ^{y}Days from planting; ^{x}Growing degree days (base temperature 0°C); ^{w}Growing degree days (base temperature 5°C); ^{v}Corn heat units; ^{u}Physiological days

Table B.2. Dates of NDVI measurement and the associated crop stages (Harper and Berkenkamp 1975), days from planting, and heat units for canola plots at Indian Head, SK.

			DFP^y	GDD$_0$^{x}	GDD$_5$^{w}	CHU^v	P-Days^u
Year	Date	Crop Stage^z	days	°C			
2005	June 5	1 – 2.1	24	258.4	142.2	229.1	139.8
	June 11	2.2 – 2.3	30	325.3	179.2	285.8	181.8
	June 19	2.4 – 2.6	38	460.8	274.7	446.6	237.7
	June 23	3.1 – 3.2	42	539.2	333.0	537.9	262.0
	June 28	3.3 – 4.1	47	605.4	374.3	607.3	296.3
	July 7	4.3 – 4.4	56	749.2	473.1	773.4	361.1
2006	June 1	1 – 2.1	16	221.8	141.8	218.5	103.8
	June 8	2.2 – 2.3	23	349.1	234.1	361.3	146.8
	June 13	2.3 – 2.5	28	401.1	261.1	400.3	182.0
	June 16	2.4 – 2.5	31	448.2	292.3	454.5	202.4
	June 22	2.6 – 3.1	37	543.8	358.8	568.3	250.2
	June 25	3.1 – 3.2	40	595.4	395.4	630.7	272.2
	June 28	3.3 – 4.1	43	643.8	428.8	686.8	293.9
	August 2	5.3	78	1274.2	884.2	1408.4	515.9

^{z}Harker and Berkenkamp 1975; ^{y}Days from planting; ^{x}Growing degree days (base temperature 0°C); ^{w}Growing degree days (base temperature 5°C); ^{v}Corn heat units; ^{u}Physiological days

Table B.3. Dates of NDVI measurement and the associated crop stages (Harper and Berkenkamp 1975), days from planting, and heat units for canola plots at Ottawa, ON.

			DFP^y	GDD$_0$^{x}	GDD$_5$^{w}	CHU^v	P-Days^u
Year	Date	Crop Stage^z	days	˚C			
2005	June 1	2.1	25	306.4	182.0	293.7	164.3
	June 3	2.1 – 2.2	27	346.0	211.6	340.4	175.4
	June 7	2.4 – 2.5	31	432.9	278.6	443.3	197.3
	June 10	6.5 – 2.7	34	491.0	321.7	513.4	216.7
	June 20	4.2	44	697.8	478.5	764.5	278.7
	June 23	4.3	47	750.8	516.5	827.0	299.3
	June 29	5.2	53	889.5	625.1	986.6	330.1
2006	May 29	2.2	17	229.4	161.7	235.7	122.9
	June 2	2.3	21	318.7	213.7	343.2	144.7
	June 5	2.4	24	371.6	251.6	407.7	166.0
	June 9	2.5	28	446.8	306.8	496.6	191.5
	June 12	2.6	31	482.1	327.1	529.9	214.0
	June 16	2.7	35	555.3	380.3	619.4	240.7
	June 19	3.1 – 3.2	38	624.2	434.2	701.8	256.5
	June 23	3.3 – 4.1	42	701.1	491.1	795.5	282.9
	June 30	4.2 – 4.3	49	843.4	598.4	971.3	325.7
	July 6	4.4 – 5.1	55	966.5	691.5	1122.5	361.6
	July 21	5.2 – 5.3	70	1303.9	953.9	1531.9	442.9

[z]Harker and Berkenkamp 1975; [y]Days from planting; [x]Growing degree days (base temperature 0˚C); [w]Growing degree days (base temperature 5˚C); [v]Corn heat units; [u]Physiological days

Table B.4. Dates of NDVI measurement and the associated crop stages (Harper and Berkenkamp 1975), days from planting, and heat units for canola plots at Scott, SK.

			DFP^y	GDD$_0$^{x}	GDD$_5$^{w}	CHU^v	P-Days^u
Year	Date	Crop Stage^z	days	˚C			
2005	June 8	2.1 – 2.2	19	207.5	112.5	175.7	125.5
	June 16	2.3	27	317.7	182.7	292.7	185.0
	June 21	2.4	32	388.6	228.6	372.4	225.3
	June 24	2.5 – 2.6	35	442.3	267.3	433.1	244.7
	June 27	3.1	38	475.9	285.9	463.4	266.2
	June 30	3.3	41	513.9	308.9	502.8	289.7
2006	June 7	2.2	19	263.6	168.6	261.2	120.9
	June 14	2.4	26	341.6	211.6	328.2	170.0
	June 16	2.4 – 2.5	28	375.6	235.6	369.9	185.0
	June 19	2.5	31	417.9	269..2	416.9	210.0
	June 22	2.5	34	462.9	292.9	468.6	233.9
	June 26	2.6 – 3.2	38	527.8	337.8	544.3	263.4
	June 30	3.3 – 4.1	42	604.7	394.7	633.2	288.5
	July 4	4.3	46	671.8	441.8	710.8	315.5
	July 6	4.3 – 4.4	48	714.3	474.3	759.0	325.9

[z]Harker and Berkenkamp 1975; [y]Days from planting; [x]Growing degree days (base temperature 0˚C); [w]Growing degree days (base temperature 5˚C); [v]Corn heat units; [u]Physiological days

Table B.5. Dates of NDVI measurement and the associated crop stages (Harper and Berkenkamp 1975), days from planting, and heat units for canola plots at Swift Current, SK.

Year	Date	Crop Stage[z]	DFP[y]	GDD$_0$[x]	GDD$_5$[w]	CHU[v]	P-Days[u]
			days	˚C			
2005	June 10	2.1	21	238.2	133.2	215.7	143.3
	June 14	2.2	25	297.2	172.2	282.8	174.1
	June 16	2.2 – 2.3	27	327.1	192.1	317.5	189.7
	June 20	2.4 – 2.5	31	394.9	239.9	397.9	217.8
	June 22	2.5 – 3.1	33	432.9	267.9	440.8	229.5
	June 27	3.2 – 4.1	38	511.1	321.1	527.9	265.1
	July 4	4.1 – 4.2	45	617.7	392.7	651.4	320.5
	July 6	4.2 – 4.3	47	652.9	417.9	692.3	333.6
	July 12	4.3 – 4.4	53	770.9	505.9	833.0	369.4
	July 18	5.1 – 5.2	59	886.2	591.2	966.5	406.4
2006	June 6	1 – 2.1	20	328.0	228.0	348.2	126.8
	June 12	2.1 – 2.1	26	403.0	273.0	421.1	171.9
	June 15	2.3 – 2.4	29	445.6	300.6	468.8	194.9
	June 19	2.3 – 2.5	33	506.7	341.7	540.2	227.0
	June 21	2.4 – 2.5	35	536.4	361.4	573.7	242.8
	June 23	2.5 – 2.6	37	566.0	381.0	607.9	258.7
	June 30	3.3 – 4.1	44	697.7	477.7	762.1	303.7
	July 4	4.2 – 4.4	48	771.3	531.3	850.7	329.2

[z] Harker and Berkenkamp 1975; [y] Days from planting; [x] Growing degree days (base temperature 0˚C); [w] Growing degree days (base temperature 5˚C); [v] Corn heat units; [u] Physiological days

APPENDIX C – DAILY HEAT ACCUMULATION AND PRECIPITATION AT BRANDON, INDIAN HEAD, OTTAWA, SCOTT, AND SWIFT CURRENT DURING THE 2005 AND 2006 GROWING SEASONS

Table C.1. Daily accumulation of various heat units and daily precipitations at Brandon, MB in 2005.

May					June					July					**August**				
Day	*GDD*[z]	*CHU*[y]	*P-Days*[x]	*Prec*[w] *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	0.0	0.0	0.0	0.4	**1**	17.4	21.6	7.4	23.0	**1**	17.5	20.9	7.1	0.0	**1**	24.2	24.6	5.0	0.0
2	0.0	0.0	0.6	0.0	**2**	17.4	21.4	7.4	26.0	**2**	19.7	23.1	5.6	6.0	**2**	26.2	29.8	4.4	0.0
3	4.2	0.0	1.2	0.0	**3**	16.5	19.0	7.1	8.0	**3**	16.3	19.8	7.9	4.0	**3**	18.9	23.4	6.3	0.0
4	7.7	4.2	2.7	0.0	**4**	16.2	19.7	8.1	0.0	**4**	16.5	20.0	7.9	0.0	**4**	17.4	20.2	6.8	0.0
5	10.5	9.3	5.5	0.0	**5**	15.8	19.0	8.2	0.0	**5**	16.8	19.8	7.2	0.0	**5**	19.4	19.0	4.8	0.0
6	8.9	6.3	3.5	0.0	**6**	15.7	18.4	7.8	0.0	**6**	22.1	26.7	5.5	2.0	**6**	22.1	23.4	5.0	0.0
7	14.1	15.8	8.2	14.0	**7**	10.1	6.4	7.3	11.0	**7**	24.2	27.9	5.0	84.0	**7**	22.1	23.2	5.0	0.0
8	10.0	5.6	7.6	16.0	**8**	10.0	5.5	7.5	13.0	**8**	22.4	26.7	5.4	0.0	**8**	20.5	25.7	6.1	0.0
9	10.2	8.2	6.1	0.0	**9**	13.4	14.6	8.0	0.0	**9**	26.9	31.4	3.9	0.0	**9**	16.5	19.5	7.4	0.0
10	2.6	0.0	0.5	0.0	**10**	15.3	17.5	7.4	3.0	**10**	23.8	30.0	5.1	15.0	**10**	15.7	17.3	6.8	0.0
11	0.4	0.0	0.3	0.0	**11**	18.5	23.3	6.6	4.0	**11**	22.9	29.2	5.5	1.0	**11**	17.3	21.5	7.5	0.0
12	3.8	0.0	0.9	1.0	**12**	17.7	21.9	7.2	2.0	**12**	23.1	26.8	5.1	0.0	**12**	13.9	15.4	7.9	0.0
13	7.1	1.9	3.3	2.0	**13**	17.2	21.4	7.6	6.0	**13**	25.0	29.8	4.6	0.0	**13**	12.4	12.7	6.7	0.0
14	3.9	0.0	0.6	0.0	**14**	15.0	17.0	8.6	14.0	**14**	21.2	26.4	5.9	0.0	**14**	14.4	16.0	7.3	0.0
15	4.0	0.0	1.1	0.0	**15**	17.4	21.2	7.3	0.0	**15**	20.7	24.5	5.6	0.0	**15**	14.5	16.6	7.9	0.0
16	10.3	9.1	5.7	0.0	**16**	20.4	25.4	6.0	0.0	**16**	21.8	26.7	5.6	2.0	**16**	15.4	17.7	7.5	0.0
17	14.0	15.3	7.07	0.0	**17**	23.7	29.7	5.2	0.0	**17**	18.9	24.1	6.4	12.0	**17**	15.6	18.6	8.3	0.0
18	18.4	22.6	6.6	0.0	**18**	22.6	26.5	5.3	8.0	**18**	16.4	19.9	8.0	0.0	**18**	13.6	14.9	8.2	2.0
19	19.7	23.6	5.7	0.0	**19**	20.7	24.4	5.5	1.0	**19**	19.5	22.9	5.6	0.0	**19**	13.0	13.7	6.7	0.0
20	20.0	23.5	5.5	0.0	**20**	20.5	24.7	5.8	0.0	**20**	16.8	20.4	7.6	0.0	**20**	12.3	12.6	6.9	0.0
21	15.9	18.9	8.0	18.0	**21**	21.1	25.9	5.8	0.0	**21**	15.9	18.5	7.5	0.0	**21**	12.9	13.7	6.9	0.0
22	16.9	20.1	7.3	0.0	**22**	23.9	27.2	5.0	0.0	**22**	17.3	19.8	6.7	0.0	**22**	16.4	18.3	6.8	0.0
23	14.3	16.0	7.6	0.0	**23**	17.4	19.2	6.4	1.0	**23**	23.4	27.4	5.1	0.0	**23**	20.2	23.1	5.3	0.0
24	14.4	15.8	6.9	0.0	**24**	12.0	12.0	6.6	0.0	**24**	20.7	25.5	5.9	0.0	**24**	20.6	26.6	6.2	0.0
25	10.7	9.5	6.2	0.0	**25**	16.6	20.2	7.9	0.0	**25**	14.3	16.1	7.9	0.0	**25**	16.9	20.2	7.5	0.0
26	9.6	5.7	6.8	0.0	**26**	18.0	21.5	6.8	46.0	**26**	14.2	15.7	7.1	1.0	**26**	15.5	18.1	7.8	0.0
27	7.5	0.7	4.3	1.0	**27**	14.1	15.8	8.3	13.0	**27**	14.3	16.3	8.1	0.0	**27**	16.5	19.2	7.2	0.0
28	9.0	5.3	5.4	1.0	**28**	16.0	19.3	8.2	0.0	**28**	15.8	18.6	7.7	0.0	**28**	16.7	18.3	6.5	0.0
29	13.1	14.1	7.7	0.0	**29**	15.2	17.7	8.5	36.0	**29**	15.7	18.2	7.5	2.0	**29**	16.4	18.2	6.6	0.0
30	12.8	13.0	6.3	0.0	**30**	16.7	20.0	7.6	10.0	**30**	21.4	24.3	5.2	0.0	**30**	18.5	21.5	6.3	0.0
31	15.5	17.1	6.8	1.0	**31**					**31**	23.7	27.4	5.1	0.0	**31**	14.1	15.8	8.4	15.0
Total	**309.0**	**281.7**	**145.9**	**54.4**	**Total**	**511.6**	**597.4**	**212.3**	**225.0**	**Total**	**608.5**	**724.6**	**194.3**	**129.0**	**Total**	**529.4**	**598.8**	**207.9**	**17.0**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z] Growing Degree Days calculated using a base temperature of 0° C; [y] Corn Heat Units; [x] Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w] Total daily amounts of precipitation

Table C.2. Daily accumulation of various heat units and daily precipitations at Brandon, MB in 2006.

	May					June					July					**August**			
Day	***GDD^z***	***CHU^y***	***P-Days^x***	***Prec^w (mm)***	***Day***	***GDD***	***CHU***	***P-Days***	***Prec (mm)***	***Day***	***GDD***	***CHU***	***P-Days***	***Prec. (mm)***	***Day***	***GDD***	***CHU***	***P-Days***	***Prec. (mm)***
1	10.2	6.8	7.4	4.0	**1**	17.2	19.6	6.7	0.0	**1**	19.6	23.4	5.7	0.0	**1**	18.5	19.2	5.4	0.0
2	9.7	7.6	5.5	1.2	**2**	19.0	19.6	5.1	0.0	**2**	19.3	22.5	5.7	2.8	**2**	20.1	22.7	5.1	11.4
3	6.8	0.0	3.4	2.4	**3**	21.9	23.1	5.0	0.2	**3**	16.8	20.1	7.5	0.0	**3**	18.8	21.4	5.9	0.0
4	2.9	0.0	0.2	T	**4**	20.6	25.4	5.9	0.2	**4**	17.2	19.7	6.7	0.0	**4**	19.3	23.0	5.8	2.4
5	9.0	6.7	4.4	0.0	**5**	18.7	22.4	6.3	6.2	**5**	19.2	21.1	5.5	0.0	**5**	20.0	24.1	5.8	0.0
6	12.2	11.4	5.7	T	**6**	19.9	23.2	5.5	0.0	**6**	21.9	23.2	5.0	0.0	**6**	17.7	21.0	6.9	0.0
7	15.2	17.3	7.4	T	**7**	15.5	17.7	7.4	0.0	**7**	25.7	28.4	4.6	1.8	**7**	17.8	17.9	5.3	0.0
8	13.6	14.1	6.5	T	**8**	10.7	8.3	7.5	4.8	**8**	20.7	25.2	5.8	T	**8**	25.5	26.5	4.8	T
9	10.7	8.8	7.1	T	**9**	12.2	11.3	8.4	2.8	**9**	15.3	17.9	7.9	0.0	**9**	23.8	29.4	5.1	0.0
10	7.1	1.6	3.4	0.4	**10**	14.7	16.9	8.4	0.0	**10**	16.1	17.3	6.4	0.0	**10**	23.8	27.7	5.0	0.0
11	5.4	0.0	1.7	0.0	**11**	12.8	12.8	8.5	0.6	**11**	23.3	26.7	5.1	0.0	**11**	23.4	27.4	5.1	19.6
12	6.7	2.5	2.5	0.0	**12**	15.5	17.6	7.3	T	**12**	22.4	22.7	5.0	T	**12**	20.0	23.4	5.5	T
13	6.6	0.0	3.1	4.8	**13**	14.7	16.2	7.0	0.0	**13**	22.7	27.7	5.4	1.0	**13**	18.9	23.7	6.3	T
14	10.8	8.9	7.3	T	**14**	18.4	20.8	6.1	0.0	**14**	22.9	25.6	5.1	0.0	**14**	17.1	19.8	7.0	0.0
15	12.8	13.6	7.2	0.0	**15**	22.1	27.0	5.6	3.4	**15**	22.9	24.3	5.1	0.0	**15**	18.8	19.3	5.2	0.0
16	12.9	11.4	5.5	0.0	**16**	22.8	26.7	5.2	T	**16**	22.1	24.7	5.1	0.0	**16**	22.8	27.1	5.3	0.0
17	12.9	13.3	6.5	0.0	**17**	20.4	24.9	5.9	4.2	**17**	18.7	21.6	6.1	0.0	**17**	18.7	22.2	6.2	0.0
18	18.1	20.6	6.3	1.0	**18**	17.3	21.1	7.3	1.2	**18**	22.0	21.2	4.7	0.0	**18**	17.0	20.2	7.2	0.0
19	14.3	15.0	6.4	0.0	**19**	17.3	19.6	6.6	0.0	**19**	20.5	25.1	5.9	0.0	**19**	18.2	19.5	5.7	0.0
20	8.7	4.7	5.1	0.0	**20**	18.9	21.8	5.9	2.0	**20**	17.5	20.0	6.6	0.0	**20**	19.0	19.6	5.1	0.0
21	7.5	3.3	3.4	0.0	**21**	16.9	20.4	7.5	8.0	**21**	20.2	22.6	5.1	1.0	**21**	16.2	18.5	7.1	0.0
22	15.3	15.4	6.0	0.0	**22**	16.1	19.2	7.9	7.6	**22**	22.0	22.9	5.0	0.0	**22**	19.2	19.3	5.0	0.0
23	23.0	24.2	5.1	0.0	**23**	17.5	21.2	7.2	1.0	**23**	24.9	25.0	4.9	0.0	**23**	20.3	23.7	5.5	0.0
24	20.2	25.8	6.2	T	**24**	16.6	19.8	7.5	10.0	**24**	21.9	24.9	5.2	T	**24**	19.1	24.5	6.4	43.0
25	16.9	20.5	7.5	0.0	**25**	17.4	19.8	6.6	0.0	**25**	21.2	24.7	5.4	1.2	**25**	18.7	22.4	6.3	0.0
26	15.2	17.5	7.6	0.2	**26**	18.3	22.3	6.7	0.0	**26**	20.1	22.2	4.9	0.0	**26**	17.5	20.1	6.7	0.0
27	13.4	14.5	8.3	14.4	**27**	16.6	19.0	7.0	0.0	**27**	22.6	25.5	5.2	0.0	**27**	19.4	19.2	4.8	0.0
28	14.0	15.7	8.3	11.0	**28**	17.9	19.9	6.2	0.0	**28**	17.5	21.5	7.3	0.0	**28**	15.8	18.2	7.4	0.0
29	14.9	17.3	8.4	1.6	**29**	22.6	24.6	5.1	0.0	**29**	16.6	19.6	7.4	0.0	**29**	15.4	16.2	6.2	0.0
30	14.9	17.1	7.9	0.0	**30**	22.5	26.9	5.4	29.4	**30**	22.5	23.5	5.0	0.0	**30**	21.3	25.2	5.5	0.0
31	15.4	16.3	6.2	T	**31**					**31**	18.7	22.1	6.2	0.0	**31**	18.1	22.0	6.8	0.0
Total	**376.7**	**351.9**	**177.6**	**41.0**	**Total**	**532.0**	**608.8**	**198.7**	**81.6**	**Total**	**634.4**	**713.0**	**176.6**	**7.8**	**Total**	**599.5**	**684.2**	**181.4**	**76.4**

Data are based on Environment Canada’s online climate data [October 4, 2007]; M – missing; T – trace precipitation

^{z}Growing Degree Days calculated using a base temperature of 0° C; ^{y}Corn Heat Units; ^{x}Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; ^{w}Total daily amounts of precipitation

Table C.3. Daily accumulation of various heat units and daily precipitations at Indian Head in 2005.

	May					June					July					August			
Day	*GDD*[z]	*CHU*[y]	*P-Days*[x]	*Prec*[w] *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	0.0	0.0	0.16	0.0	**1**	13.7	14.9	8.5	2.4	**1**	17.0	20.2	7.3	12.4	**1**	24.5	26.7	5.0	0.0
2	0.0	0.0	0.42	0.0	**2**	15.4	18.2	8.2	8.6	**2**	17.4	21.0	7.2	5.0	**2**	20.1	22.8	5.2	0.0
3	3.6	0.0	1.14	0.0	**3**	15.1	17.4	7.7	0.2	**3**	15.0	17.4	8.1	2.8	**3**	15.9	18.8	7.7	0.0
4	10.6	9.5	5.49	0.0	**4**	13.4	14.2	8.6	2.2	**4**	16.6	20.1	7.8	0.2	**4**	16.7	19.4	7.1	0.0
5	8.25	5.3	3.57	0.0	**5**	11.5	10.8	7.2	1.6	**5**	18.9	23.1	6.3	3.8	**5**	21.8	23.0	5.0	0.0
6	12.0	12.1	6.61	0.2	**6**	12.0	12.0	6.4	0.2	**6**	20.0	23.8	5.6	0.0	**6**	18.4	19.6	5.7	0.0
7	13.7	14.5	6.54	0.2	**7**	9.4	5.0	6.7	8.8	**7**	19.3	23.4	5.9	0.2	**7**	21.6	21.3	4.7	0.0
8	11.0	9.3	7.47	0.0	**8**	8.4	1.9	6.0	8.6	**8**	18.9	21.7	5.9	0.0	**8**	14.2	16.0	7.9	1.8
9	10.5	9.3	5.89	0.0	**9**	11.6	11.0	7.4	0.0	**9**	23.5	27.3	5.1	0.0	**9**	14.3	16.0	7.5	0.2
10	3.4	0.0	0.72	0.0	**10**	14.2	16.1	8.3	7.2	**10**	16.4	19.9	7.9	4.8	**10**	12.8	13.5	6.8	0.6
11	0.0	0.0	0.76	0.0	**11**	14.3	15.8	7.1	0.0	**11**	18.6	22.1	6.3	0.2	**11**	13.0	13.9	7.8	0.4
12	2.4	0.0	0.88	0.6	**12**	17.0	20.2	7.3	0.0	**12**	19.8	22.4	5.2	0.0	**12**	10.6	9.1	6.4	1.6
13	4.3	0.0	1.03	0.4	**13**	14.9	17.3	8.2	0.0	**13**	24.2	29.5	4.9	2.2	**13**	10.5	9.3	5.9	0.2
14	4.5	0.0	1.07	0.0	**14**	14.8	17.2	8.2	0.0	**14**	17.1	20.5	7.4	3.0	**14**	13.9	15.4	7.6	0.0
15	6.5	1.7	2.51	0.2	**15**	14.9	16.6	7.1	5.6	**15**	18.3	21.0	6.3	0.0	**15**	11.5	11.2	6.5	0.8
16	13.7	14.7	6.70	0.0	**16**	19.2	23.5	6.0	0.4	**16**	20.3	25.4	6.1	10.8	**16**	13.3	14.3	7.4	0.0
17	12.2	12.2	7.86	5.0	**17**	20.5	25.2	5.9	19.4	**17**	14.7	16.8	8.5	2.0	**17**	16.7	19.7	7.3	1.4
18	10.2	7.5	6.89	15.6	**18**	20.1	25.0	6.0	12.0	**18**	14.6	16.4	7.5	0.0	**18**	12.0	11.9	7.3	24.6
19	15.1	16.6	6.74	0.4	**19**	16.8	20.4	7.7	0.0	**19**	15.7	18.5	8.0	0.0	**19**	11.3	10.3	7.3	1.6
20	16.1	18.3	7.04	0.0	**20**	17	19.2	6.7	0.0	**20**	13.5	14.8	7.6	0.0	**20**	12.4	12.8	6.9	0.2
21	12.1	11.6	8.22	22.8	**21**	19.7	22.4	5.2	0.0	**21**	15.8	18.5	7.6	2.4	**21**	14.2	14.9	6.5	0.2
22	15.0	17.1	7.59	0.0	**22**	24.9	29.3	4.7	10.4	**22**	14.6	16.3	7.1	0.0	**22**	22.2	23.8	5.1	0.0
23	13.2	14.3	7.54	6.4	**23**	16.0	18.6	7.5	1.0	**23**	19.6	23.5	5.7	0.2	**23**	21.0	25.3	5.7	0.2
24	10.0	7.6	6.17	0.0	**24**	9.4	6.4	5.7	0.0	**24**	14.5	16.6	8.0	0.0	**24**	15.9	18.9	7.8	5.8
25	10.0	6.9	5.76	0.6	**25**	11.6	11.4	6.3	5.0	**25**	10.7	9.7	6.1	0.0	**25**	12.4	12.4	8.2	0.4
26	7.2	0.0	4.01	0.2	**26**	17.5	21.6	7.3	0.2	**26**	12.1	12.0	6.2	0.0	**26**	12.6	13.0	8.0	0.6
27	8.4	4.0	4.94	0.2	**27**	11.8	11.4	7.6	0.0	**27**	10.2	8.3	6.2	1.4	**27**	14.7	16.2	6.9	0.2
28	7.0	0.8	3.49	4.4	**28**	9.6	6.9	5.7	1.4	**28**	11.9	11.9	6.6	0.0	**28**	17.3	19.1	6.4	0.0
29	10.2	8.2	6.17	0.2	**29**	13.9	15.0	8.7	4.0	**29**	16.8	19.2	6.9	7.6	**29**	19.2	20.0	5.1	0.2
30	10.1	8.7	5.50	0.0	**30**	15.7	18.6	8.0	0.0	**30**	19.0	22.0	5.9	0.2	**30**	18.7	20.9	5.9	12.8
31	13.5	14.5	6.76	0.2	**31**					**31**	19.2	21.0	5.4	0.0	**31**	8.9	3.6	6.2	44.2
Total	**273.8**	**224.5**	**145.6**	**57.6**	**Total**	**443.7**	**483.4**	**211.9**	**99.2**	**Total**	**523.4**	**604.1**	**206.3**	**59.2**	**Total**	**482.0**	**513.1**	**204.3**	**98.0**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z]Growing Degree Days calculated using a base temperature of 0° C; [y]Corn Heat Units; [x]Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w]Total daily amounts of precipitation

Table C.4. Daily accumulation of various heat units and daily precipitations at Indian Head, SK in 2006.

May					June					July					August				
Day	*GDD*[z]	*CHU*[y]	*P-Days*[x]	*Prec*[w] *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	6.3	0.0	2.74	0.6	**1**	16.0	17.6	6.7	0.0	**1**	16.4	19.2	7.5	0.0	**1**	16.2	17.9	6.7	0.0
2	8.4	3.6	5.04	0.2	**2**	21.5	20.9	4.7	0.0	**2**	17.1	20.1	7.1	0.0	**2**	15.2	16.5	6.6	0.0
3	2.3	0.0	0.00	2.2	**3**	22.3	26.3	5.3	1.0	**3**	15.0	16.9	7.3	0.0	**3**	14.6	15.7	6.6	5.0
4	4.6	0.0	1.26	0.0	**4**	19.5	22.0	5.3	0.0	**4**	17.2	20.0	6.9	0.0	**4**	17.7	20.9	6.9	0.0
5	11.8	11.6	6.32	0.0	**5**	18.7	22.8	6.4	16.2	**5**	17.2	18.7	6.2	0.0	**5**	15.2	17.7	7.9	0.0
6	14.7	14.9	6.19	0.0	**6**	15.7	18.0	7.4	0.2	**6**	20.7	25.5	5.9	0.0	**6**	15.5	17.6	7.3	0.0
7	12.2	12.4	6.61	0.0	**7**	13.8	15.1	7.3	0.0	**7**	21.2	24.6	5.4	0.0	**7**	17.0	16.2	5.3	0.0
8	11.4	11.0	6.32	10.2	**8**	10.2	7.5	6.9	5.4	**8**	15.5	17.7	7.3	0.0	**8**	22.2	22.8	5.0	0.0
9	6.7	0.0	3.40	0.0	**9**	10.1	6.3	7.4	5.0	**9**	13.2	14.2	7.1	0.0	**9**	19.9	22.0	4.9	0.0
10	5.9	0.0	2.38	0.6	**10**	9.6	5.0	7.0	6.0	**10**	19.7	23.1	5.5	0.0	**10**	21.8	25.2	5.3	0.2
11	5.0	0.0	1.27	0.0	**11**	11.3	10.3	7.4	1.8	**11**	20.4	24.6	5.8	0.2	**11**	22.6	25.2	5.2	1.0
12	7.3	3.5	2.95	0.0	**12**	10.9	9.8	6.6	0.2	**12**	20.0	23.1	5.4	0.0	**12**	14.7	16.7	7.6	0.0
13	9.3	7.1	5.05	0.0	**13**	12.9	13.5	6.6	0.0	**13**	19.5	24.5	6.2	0.8	**13**	14.7	16.4	7.3	0.2
14	8.7	5.1	4.97	0.0	**14**	15.9	18.0	7.1	4.4	**14**	19.1	22.8	6.0	0.2	**14**	15.3	16.3	6.3	0.0
15	9.4	7.3	4.52	0.0	**15**	18.4	22.7	6.7	6.6	**15**	19.7	21.4	5.0	0.0	**15**	19.4	18.8	4.8	0.0
16	16.7	17.6	6.05	0.0	**16**	16.3	19.4	7.7	0.6	**16**	16.6	18.7	6.8	0.0	**16**	14.9	16.9	7.4	0.0
17	12.7	12.5	6.13	0.0	**17**	15.9	19.1	8.2	0.8	**17**	15.9	17.8	6.9	0.0	**17**	16.2	18.2	6.9	0.0
18	19.8	20.8	4.82	0.4	**18**	16.3	19.6	7.9	12.0	**18**	20.8	23.4	5.2	0.4	**18**	15.5	16.6	6.3	0.0
19	14.8	15.7	6.36	0.0	**19**	16.6	19.8	7.5	0.2	**19**	16.2	19.1	7.6	0.0	**19**	18.2	20.7	6.3	0.0
20	9.9	7.8	5.91	0.0	**20**	16.3	19.7	7.9	3.8	**20**	15.7	17.5	7.0	0.0	**20**	15.7	17.4	6.8	0.0
21	12.9	13.6	7.10	0.0	**21**	14.4	16.1	8.6	3.0	**21**	17.9	19.9	6.2	0.0	**21**	14.2	14.5	6.3	0.0
22	20.4	21.6	4.73	0.0	**22**	17.2	20.8	7.3	0.2	**22**	20.8	23.4	5.2	0.0	**22**	21.9	22.4	4.9	0.0
23	19.2	22.4	5.82	1.4	**23**	17.8	21.5	7.0	0.4	**23**	23.2	25.7	5.1	0.0	**23**	23.8	26.0	5.1	0.0
24	14.9	17.2	8.54	0.8	**24**	16.6	20.1	7.7	12.0	**24**	19.1	22.0	5.8	0.2	**24**	14.2	16.0	8.4	0.8
25	12.2	12.5	6.70	0.0	**25**	17.0	19.9	7.2	0.2	**25**	18.3	21.6	6.5	0.2	**25**	16.5	18.6	6.8	0.2
26	11.3	9.9	7.68	2.6	**26**	16.3	19.1	7.5	0.0	**26**	17.8	19.7	6.2	0.0	**26**	16.7	18.8	6.7	0.0
27	8.3	2.3	5.54	0.2	**27**	15.3	17.0	7.0	0.0	**27**	19.8	22.8	5.4	0.0	**27**	18.2	19.5	5.7	0.0
28	8.9	3.4	6.41	18.4	**28**	19.3	22.1	5.6	0.0	**28**	12.9	13.2	8.4	3.2	**28**	14.5	14.3	6.1	0.0
29	10.5	8.0	7.26	0.8	**29**	23.7	27.9	5.0	0.0	**29**	13.6	14.9	8.3	0.0	**29**	21.3	23.8	5.1	0.0
30	13.8	15.2	7.68	0.0	**30**	15.3	17.8	8.0	0.4	**30**	20.2	21.4	4.7	0.4	**30**	22.6	25.7	5.2	0.0
31	15.9	18.0	7.03	0.6	**31**					**31**	15.7	18.1	7.5	0.0	**31**	11.8	11.6	6.9	4.4
Total	**345.3**	**295.2**	**162.8**	**39.0**	**Total**	**480.2**	**536.1**	**208.7**	**80.4**	**Total**	**556.0**	**635.8**	**196.7**	**5.6**	**Total**	**537.6**	**587.0**	**194.3**	**11.8**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z] Growing Degree Days calculated using a base temperature of 0° C; [y] Corn Heat Units; [x] Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w] Total daily amounts of precipitation

Table C.5. Daily accumulation of various heat units and daily precipitations at Ottawa, ON in 2005.

	May					June					July					**August**			
Day	*GDD*^{z}	*CHU*^{y}	*P-Days*^{x}	*Prec*^{w} *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	8.3	3.6	4.9	0.6	**1**	19.5	23.5	5.8	7.8	**1**	22.0	26.4	5.5	5.8	**1**	21.8	27.5	5.8	0.6
2	5.0	0.0	1.7	4.7	**2**	20.2	23.2	5.4	0.0	**2**	18.2	21.9	6.7	0.0	**2**	25.1	27.4	4.8	0.0
3	5.6	0.0	2.2	0.0	**3**	21.4	25.6	5.6	0.0	**3**	19.4	23.0	5.7	0.0	**3**	24.9	29.9	4.6	1.0
4	7.4	1.5	3.9	0.0	**4**	21.7	25.6	5.5	0.0	**4**	23.5	28.2	5.1	3.0	**4**	26.5	29.3	4.4	0.6
5	7.9	4.2	3.7	0.0	**5**	21.8	26.0	5.5	1.0	**5**	21.7	28.3	5.9	6.4	**5**	21.9	26.8	5.7	0.0
6	11.3	10.8	6.2	0.0	**6**	22.1	25.8	5.3	2.8	**6**	20.5	25.8	6.1	0.2	**6**	20.1	23.2	5.4	0.0
7	12.6	13.2	7.1	0.0	**7**	21.1	26.4	5.9	0.0	**7**	19.9	24.8	6.1	0.0	**7**	21.7	23.8	5.1	0.0
8	13.9	15.1	7.0	0.0	**8**	16.0	19.3	8.2	1.8	**8**	20.3	26.0	6.2	2.2	**8**	24.3	26.6	5.0	0.0
9	14.3	15.7	7.0	0.0	**9**	21.1	24.3	5.3	0.0	**9**	22.9	28.3	5.4	10.8	**9**	25.0	27.9	4.8	0.0
10	19.0	21.3	5.7	0.8	**10**	25.0	30.4	4.6	0.4	**10**	24.5	28.6	4.9	0.0	**10**	26.1	30.1	4.4	14.8
11	12.9	13.1	6.3	2.2	**11**	25.2	28.6	4.7	0.0	**11**	27.3	31.4	3.8	0.0	**11**	23.1	28.8	5.4	0.2
12	4.4	0.0	1.0	0.0	**12**	26.4	32.6	3.8	0.0	**12**	26.5	32.1	3.9	0.0	**12**	20.4	26.7	6.3	2.2
13	6.1	0.2	2.5	0.0	**13**	25.7	33.1	4.1	0.0	**13**	25.1	30.4	4.5	43.0	**13**	24.2	30.4	5.0	0.0
14	8.0	0.5	5.5	5.6	**14**	23.6	29.8	5.2	33.4	**14**	22.7	28.3	5.5	0.4	**14**	20.1	25.6	6.2	0.4
15	13.5	14.7	7.8	0.8	**15**	20.2	26.0	6.3	21.2	**15**	22.5	27.3	5.4	0.0	**15**	20.5	24.8	5.8	0.0
16	9.1	5.4	5.6	0.0	**16**	16.8	20.7	7.8	0.2	**16**	24.3	28.9	4.9	6.0	**16**	22.0	26.5	5.5	0.0
17	8.8	5.2	5.2	0.0	**17**	14.4	15.8	8.7	19.4	**17**	25.5	32.6	4.2	3.6	**17**	16.2	19.0	7.5	0.0
18	9.1	5.7	5.4	1.1	**18**	14.6	16.5	8.6	0.0	**18**	27.1	33.0	3.5	0.0	**18**	14.7	17.0	8.1	0.0
19	11.0	10.3	6.0	0.0	**19**	15.2	17.8	8.2	0.0	**19**	26.2	31.5	4.1	0.0	**19**	15.2	17.8	8.4	9.4
20	13.5	14.7	7.4	0.0	**20**	17.2	20.0	6.9	0.0	**20**	22.2	27.9	5.7	0.0	**20**	20.0	26.1	6.4	6.2
21	11.2	10.0	7.4	1.8	**21**	20.5	24.9	5.8	2.0	**21**	24.5	28.5	4.9	0.0	**21**	21.4	26.3	5.8	1.8
22	10.0	6.1	7.3	3.0	**22**	15.3	17.9	8.0	0.2	**22**	21.4	26.3	5.8	0.0	**22**	17.7	22.1	7.6	0.0
23	9.8	6.0	7.0	8.7	**23**	16.3	18.6	7.1	0.0	**23**	20.0	24.4	5.9	0.0	**23**	16.4	19.9	8.0	0.0
24	13.7	15.0	8.3	1.5	**24**	21.6	24.6	5.2	0.0	**24**	18.8	22.5	6.2	0.0	**24**	17.7	21.2	6.9	0.0
25	16.6	19.7	7.5	0.0	**25**	25.2	28.7	4.7	5.4	**25**	26.8	31.3	4.1	0.0	**25**	19.6	22.8	5.4	0.0
26	14.2	16.1	8.2	0.0	**26**	23.5	27.6	5.1	0.0	**26**	20.1	25.7	6.3	2.2	**26**	19.5	22.5	5.5	0.0
27	12.6	12.3	8.5	3.8	**27**	25.6	28.8	4.6	0.0	**27**	14.8	17.2	8.3	0.6	**27**	20.4	24.0	5.5	0.0
28	14.7	16.8	7.7	0.8	**28**	26.7	31.1	4.1	0.0	**28**	16.2	18.6	7.1	0.0	**28**	23.4	28.0	5.2	3.0
29	15.4	18.1	7.9	0.0	**29**	23.6	30.1	5.2	0.0	**29**	18.2	22.0	6.7	0.0	**29**	22.8	26.2	5.2	0.0
30	16.0	19.2	8.1	0.7	**30**	23.2	28.5	5.3	0.0	**30**	18.7	22.7	6.3	0.0	**30**	21.5	26.4	5.8	0.0
31	16.6	19.2	7.1	0.0	**31**					**31**	17.8	21.2	6.8	0.0	**31**	20.7	27.1	6.2	27.6
Total	**351.7**	**313.7**	**186.8**	**36.1**	**Total**	**629.9**	**751,6**	**176.4**	**95.6**	**Total**	**679.1**	**824.7**	**271.2**	**84.2**	**Total**	**654.1**	**781.8**	**181.1**	**67.8**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

^{z}Growing Degree Days calculated using a base temperature of 0° C; ^{y}Corn Heat Units; ^{x}Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; ^{w}Total daily amounts of precipitation

Table C.6. Daily accumulation of various heat units and daily precipitations at Ottawa, ON in 2006.

	May					June					July					**August**			
Day	***GDD***[z]	***CHU***[y]	***P-Days***[x]	***Prec***[w] ***(mm)***	***Day***	***GDD***	***CHU***	***P-Days***	***Prec (mm)***	***Day***	***GDD***	***CHU***	***P-Days***	***Prec. (mm)***	***Day***	***GDD***	***CHU***	***P-Days***	***Prec. (mm)***
1	15.5	17.5	7.2	0.0	**1**	18.5	22.9	6.6	4.5	**1**	19.7	23.8	5.8	21.5	**1**	29.1	30.6	3.2	17.3
2	12.5	12.9	7.8	0.7	**2**	18.6	22.3	6.3	0.0	**2**	23.3	28.3	5.2	2.3	**2**	24.7	30.0	4.7	56.5
3	12.1	12.0	7.7	0.0	**3**	16.2	19.5	8.1	7.9	**3**	21.5	24.7	5.3	9.4	**3**	23.2	29.2	5.4	1.2
4	14.1	14.6	6.4	7.1	**4**	18.2	22.7	6.8	0.0	**4**	22.3	28.6	5.7	0.0	**4**	23.2	28.2	5.3	1.3
5	12.9	13.6	7.8	0.0	**5**	18.3	20.4	6.1	0.0	**5**	19.0	24.4	6.4	1.6	**5**	18.8	23.4	6.3	0.0
6	5.1	0.0	1.8	8.7	**6**	20.2	23.6	5.5	0.0	**6**	18.5	23.4	6.6	M	**6**	20.1	24.2	5.8	0.0
7	6.6	1.1	2.9	0.0	**7**	20.4	24.9	5.9	0.0	**7**	21.2	25.6	5.7	0.0	**7**	23	28.1	5.3	1.5
8	13.3	14.0	6.6	1.0	**8**	16.4	20.0	8.0	0.9	**8**	21.9	26.5	5.6	0.0	**8**	17.9	22.01	7.0	0.0
9	15.3	16.8	6.8	0.0	**9**	13.2	14.2	8.1	9.7	**9**	21.4	25.9	5.7	0.0	**9**	18.6	21.89	6.2	0.0
10	16.6	20.0	7.7	0.0	**10**	9.9	6.7	6.8	4.5	**10**	22.4	28.0	5.6	3	**10**	19.3	24.26	6.2	0.0
11	18.0	21.6	6.8	0.0	**11**	12.2	12.3	7.6	1.3	**11**	22.0	27.8	5.8	0.0	**11**	15	17.42	8.0	0.7
12	14.2	15.7	8.7	30.6	**12**	17.6	21.6	7.2	0.0	**12**	21.1	27.3	6.1	0.0	**12**	14.95	17.21	7.7	0.0
13	12.6	12.1	8.6	3.5	**13**	18.0	22.4	7.0	M	**13**	23.0	26.8	5.1	0.0	**13**	16.65	19.36	7.2	0.0
14	12.2	11.5	8.3	3.2	**14**	18.5	22.4	6.5	0.0	**14**	25.8	31.0	4.3	0.0	**14**	19.55	23.78	5.9	0.9
15	14.5	16.6	8.4	2.8	**15**	19.1	23.1	6.0	0.0	**15**	24.2	30.1	4.9	1.7	**15**	20.45	25.92	6.1	0.0
16	15.6	18.6	8.2	2.5	**16**	22.4	26.4	5.3	0	**16**	25.6	28.8	4.6	0.0	**16**	18.85	23.09	6.3	0.0
17	14.9	17.2	8.5	5.4	**17**	21.8	27.0	5.7	13.3	**17**	26.0	29.9	4.4	8.9	**17**	18.65	21.67	6.1	0.0
18	14.2	15.9	8.6	8.9	**18**	24.8	29.0	4.8	0.0	**18**	21.1	26.6	6.0	0.0	**18**	21.85	25.49	5.3	0.0
19	13.2	13.6	8.6	2.3	**19**	21.0	26.6	6.0	11.5	**19**	20.7	25.1	5.8	0.0	**19**	23.65	29.39	5.1	0.0
20	9.2	4.5	6.4	4.8	**20**	16.3	19.7	8.0	0.7	**20**	23.0	26.6	5.1	0.0	**20**	17.45	21.92	7.4	M
21	8.7	4.4	5.2	4.2	**21**	17.1	20.0	7.1	0.0	**21**	21.4	27.1	5.9	0.0	**21**	18.45	22.51	6.6	0.0
22	7.7	1.9	4.3	0.0	**22**	22.7	27.4	5.4	4.7	**22**	18.7	23.9	6.5	0.0	**22**	19.4	24.27	6.2	0.0
23	11.2	10.3	7.1	0.0	**23**	16.8	20.5	7.7	0.0	**23**	19.0	23.1	6.2	0.0	**23**	15.4	18.18	8.1	0.0
24	10.5	9.3	5.3	0.0	**24**	17.5	20.5	6.9	0.0	**24**	18.5	22.3	6.4	0.0	**24**	16.6	20.27	7.8	0.0
25	17.1	19.2	6.7	0.0	**25**	19.7	22.9	5.5	0.0	**25**	23.3	29.3	5.3	18.6	**25**	15.55	18.43	8.1	0.0
26	18.2	23.1	6.8	0.0	**26**	21.4	27.3	6.0	0.7	**26**	23.3	28.4	5.2	0.0	**26**	14.95	17.15	7.7	0.0
27	17.8	21.5	6.9	0.0	**27**	23.6	29.7	5.2	33.2	**27**	25.0	31.1	4.6	1.7	**27**	17.8	22.51	7.1	19.3
28	18.1	20.4	6.3	1.0	**28**	22.9	28.8	5.5	0.0	**28**	23.0	29.0	5.4	0.0	**28**	18.3	22.73	6.7	0.0
29	22.3	27.3	5.6	M	**29**	20.7	26.0	6.0	7.8	**29**	23.7	28.7	5.1	0.6	**29**	20.2	25.22	6.0	M
30	24.9	29.3	4.7	0.0	**30**	17.4	21.6	7.4	6.6	**30**	19.6	24.4	6.1	0.0	**30**	14.8	17.16	8.2	0.0
31	23.6	27.9	5.0	M	**31**					**31**	23.7	27.9	5.0	20.5	**31**	16	18.87	7.6	0.0
Total	**442.0**	**464.5**	**207.5**	**86.7**	**Total**	**560.6**	**672.5**	**195.0**	**107.3**	**Total**	**682.0**	**834.0**	**171.5**	**89.8**	**Total**	**592.3**	**714.4**	**200.6**	**98.7**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z] Growing Degree Days calculated using a base temperature of 0° C; [y] Corn Heat Units; [x] Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w] Total daily amounts of precipitation

Table C.7. Daily accumulation of various heat units and daily precipitations at Scott, SK, 2005.

May					June					July					**August**				
Day	*GDD*[z]	*CHU*[y]	*P-Days*[x]	*Prec*[w] *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	0.0	0.0	0.0	0.0	**1**	14.4	16.4	8.4	0.6	**1**	17.6	21.4	7.2	11.0	**1**	19.4	22.9	5.7	0.0
2	0.2	0.0	0.6	0.0	**2**	12.8	12.8	8.5	18.8	**2**	15.6	18.5	8.0	0.4	**2**	16.8	20.0	7.4	0.0
3	5.2	0.0	1.3	0.0	**3**	12.4	11.9	8.4	2.6	**3**	13.5	14.5	8.4	11.6	**3**	15.2	17.6	7.8	0.0
4	8.6	5.6	4.5	0.0	**4**	11.1	9.0	7.9	0.0	**4**	14.8	16.4	7.1	0.0	**4**	15.8	17.0	6.4	0.0
5	8.3	5.5	3.4	0.0	**5**	10.2	7.6	6.8	0.4	**5**	18.1	21.0	6.5	0.0	**5**	18.6	19.5	5.4	0.0
6	10.4	8.0	7.1	0.8	**6**	10.5	8.7	6.6	0.0	**6**	20.5	24.0	5.5	0.0	**6**	18.7	22.1	6.3	0.0
7	9.1	5.8	5.5	0.0	**7**	9.0	3.9	6.3	2.8	**7**	17.0	20.7	7.6	0.0	**7**	17.8	21.3	6.9	0.0
8	9.8	7.6	5.7	0.0	**8**	7.9	0.5	5.3	0.4	**8**	18.5	20.6	5.9	0.0	**8**	14.4	16.4	8.2	0.0
9	12.4	12.8	7.5	0.0	**9**	12.5	12.8	7.7	0.0	**9**	17.0	21.0	7.7	0.0	**9**	11.8	11.6	6.3	0.2
10	2.7	0.0	0.6	0.0	**10**	14.0	15.4	7.3	0.0	**10**	16.4	19.0	7.2	0.4	**10**	8.7	5.3	4.9	0.0
11	3.4	0.0	1.1	0.0	**11**	15.1	17.1	7.4	0.2	**11**	16.0	18.5	7.4	0.0	**11**	11.6	11.2	6.7	0.8
12	9.0	6.6	4.2	0.0	**12**	16.1	19.0	7.7	14.0	**12**	19.6	22.5	5.4	0.0	**12**	9.6	6.5	6.2	3.0
13	4.6	0.0	1.2	0.0	**13**	14.8	17.2	8.3	16.0	**13**	19.9	23.5	5.6	19.0	**13**	11.0	10.3	5.9	0.6
14	5.9	0.8	1.8	0.0	**14**	15.3	18.0	8.2	0.0	**14**	16.8	20.2	7.6	2.4	**14**	13.7	15.2	8.1	0.0
15	12.6	13.0	6.5	0.0	**15**	14.8	16.9	7.7	0.8	**15**	15.7	17.7	7.1	0.0	**15**	9.3	5.2	6.3	1.6
16	16.3	17.9	6.5	3.4	**16**	13.4	14.5	7.4	0.0	**16**	16.3	19.9	8.1	0.2	**16**	8.9	3.4	6.4	6.0
17	12.3	11.9	8.3	14.0	**17**	14.5	16.5	8.6	21.8	**17**	16.8	20.5	7.7	5.0	**17**	9.3	4.9	6.5	13.6
18	12.8	13.2	8.2	0.2	**18**	15.4	18.1	7.9	3.8	**18**	17.9	20.2	6.4	0.2	**18**	8.6	4.3	5.1	0.2
19	14.8	16.7	7.4	0.0	**19**	13.7	15.1	8.4	1.8	**19**	15.0	17.4	8.0	0.0	**19**	11.0	9.8	6.9	5.2
20	13.7	14.9	7.1	0.0	**20**	14.0	15.6	7.0	0.0	**20**	10.8	9.8	6.2	0.4	**20**	11.5	11.1	6.0	0.0
21	10.9	9.0	7.5	20.4	**21**	18.4	20.8	6.1	0.0	**21**	14.7	16.7	7.6	0.0	**21**	17.1	19.6	6.8	0.0
22	11.9	11.8	6.3	0.0	**22**	22.5	26.6	5.3	0.0	**22**	16.5	19.5	7.5	0.2	**22**	15.5	18.0	7.7	0.0
23	11.1	9.7	7.5	1.4	**23**	12.8	13.3	8.1	1.8	**23**	17.2	20.9	7.4	0.8	**23**	11.9	11.0	8.1	19.4
24	9.8	6.6	6.5	1.2	**24**	10.2	8.0	6.5	0.0	**24**	10.3	7.8	6.9	0.4	**24**	12.5	12.1	8.5	37.4
25	7.9	2.7	4.5	0.0	**25**	10.8	9.4	6.7	3.4	**25**	11.3	10.7	6.4	0.0	**25**	10.8	8.0	7.9	0.6
26	7.9	3.2	4.4	0.0	**26**	12.7	12.9	8.3	8.4	**26**	13.2	14.2	7.8	0.0	**26**	13.9	15.4	7.5	0.0
27	9.4	7.0	5.3	0.0	**27**	13.1	14.0	7.5	0.2	**27**	13.2	14.2	8.2	7.4	**27**	15.6	16.9	6.5	0.0
28	8.2	3.4	4.7	0.0	**28**	12.1	11.8	7.9	0.0	**28**	13.9	15.5	8.0	12.0	**28**	18.0	20.3	6.3	0.0
29	9.8	8.1	5.4	0.0	**29**	12.9	13.6	8.1	2.2	**29**	17.8	21.1	6.9	0.6	**29**	18.8	20.9	5.8	0.0
30	12.9	13.4	6.6	0.0	**30**	15.0	17.0	7.4	0.0	**30**	19.1	23.2	6.0	4.8	**30**	11.3	10.1	7.6	0.0
31	14.2	15.6	7.0	0.0	**31**					**31**	21.4	24.2	5.2	0.0	**31**	12.7	13.3	7.0	0.0
Total	**285.3**	**230.7**	**154.5**	**41.4**	**Total**	**401.5**	**414.4**	**224.4**	**100.0**	**Total**	**501.4**	**575.2**	**218.3**	**76.8**	**Total**	**419.1**	**421.0**	**209.1**	**88.6**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z]Growing Degree Days calculated using a base temperature of 0° C; [y]Corn Heat Units; [x]Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w]Total daily amounts of precipitation

Table C.8. Daily accumulation of various heat units and daily precipitations at Scott, SK, 2006.

	May					June					July					August			
Day	*GDD*[z]	*CHU*[y]	*P-Days*[x]	*Prec*[w] *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	4.3	0.0	1.0	4.8	**1**	16.6	18.1	6.5	21.2	**1**	17.2	20.1	7.0	0.0	**1**	15.8	17.9	7.1	0.0
2	1.8	0.0	0.0	5.4	**2**	19.2	21.0	5.4	0.0	**2**	17.0	20.4	7.4	0.0	**2**	15.0	17.1	7.4	2.4
3	0.0	0.0	0.0	0.2	**3**	16.9	20.0	7.3	0.0	**3**	18.8	21.9	6.0	0.0	**3**	13.1	14.0	7.1	0.0
4	4.4	0.0	1.2	0.0	**4**	16.5	18.5	6.8	0.0	**4**	20.3	23.3	5.3	0.4	**4**	15.4	17.4	7.2	27.8
5	13.4	14.1	6.5	0.0	**5**	19.1	23.5	6.1	0.0	**5**	22.2	24.9	5.2	0.0	**5**	14.8	17.2	8.2	0.4
6	13.3	13.8	6.5	0.0	**6**	13.9	15.5	7.9	0.0	**6**	19.1	23.7	6.1	0.0	**6**	15.6	17.2	6.8	0.0
7	12.2	12.5	7.1	0.0	**7**	12.4	12.8	6.6	0.0	**7**	18.1	21.6	6.7	11.6	**7**	19.9	20.8	4.7	0.0
8	7.8	2.7	4.3	1.6	**8**	11.5	10.4	7.8	13.8	**8**	16.9	20.5	7.5	0.8	**8**	20.9	23.2	5.0	0.0
9	4.8	0.0	1.5	2.0	**9**	9.6	5.2	7.0	6.0	**9**	18.1	20.8	6.4	0.0	**9**	21.1	25.9	5.8	0.0
10	7.3	1.5	3.8	0.0	**10**	11.4	9.8	8.1	1.2	**10**	20.9	24.9	5.6	3.6	**10**	20.3	25.7	6.1	0.0
11	7.7	3.7	3.5	0.0	**11**	9.8	6.2	6.8	0.2	**11**	18.3	22.6	6.7	1.0	**11**	17.4	21.4	7.5	7.0
12	11.7	11.3	7.1	1.2	**12**	10.3	8.7	6.1	0.2	**12**	20.9	24.2	5.4	0.0	**12**	13.5	14.7	8.1	0.4
13	11.0	9.6	7.2	0.8	**13**	13.1	13.9	6.8	0.0	**13**	18.7	23.0	6.4	2.8	**13**	14.5	16.1	7.0	1.4
14	11.5	11.1	6.3	0.0	**14**	16.5	19.8	7.7	0.0	**14**	16.9	20.1	7.3	0.0	**14**	16.7	18.5	6.6	0.2
15	14.4	15.6	6.7	0.0	**15**	17.6	21.9	7.3	7.4	**15**	18.9	22.1	6.0	3.4	**15**	15.7	18.1	7.5	0.0
16	15.9	17.5	6.6	0.0	**16**	14.2	16.0	7.8	1.6	**16**	16.6	20.1	7.8	0.0	**16**	14.5	16.4	7.6	0.0
17	19.0	19.6	5.1	0.0	**17**	13.5	14.3	8.7	1.4	**17**	16.9	19.1	6.8	0.0	**17**	15.7	17.7	7.0	0.0
18	19.0	22.7	6.0	0.0	**18**	14.6	16.7	8.4	4.2	**18**	17.1	20.8	7.5	0.0	**18**	17.9	20.3	6.3	0.0
19	15.2	17.1	7.3	0.0	**19**	15.5	17.6	7.3	0.8	**19**	15.0	17.1	7.5	0.0	**19**	18.0	20.3	6.4	0.0
20	10.5	8.9	6.5	0.0	**20**	14.5	16.4	8.5	8.6	**20**	18.1	20.3	6.2	0.0	**20**	15.2	17.7	7.9	3.6
21	15.6	17.3	6.9	1.6	**21**	15.1	17.6	8.1	0.0	**21**	20.9	22.8	5.0	0.0	**21**	17.4	19.0	6.7	0.0
22	19.8	21.0	4.8	13.6	**22**	16.5	19.6	7.5	0.0	**22**	22.4	23.8	5.1	0.0	**22**	19.9	19.5	4.6	0.0
23	18.7	23.5	6.5	3.6	**23**	16.1	19.1	7.8	0.0	**23**	23.0	25.3	5.1	0.0	**23**	18.3	22.5	6.7	0.2
24	11.2	9.8	7.5	2.6	**24**	15.7	18.2	7.5	0.0	**24**	22.3	27.3	5.5	4.6	**24**	15.8	18.7	7.9	2.8
25	11.2	10.5	6.4	0.6	**25**	16.7	18.8	6.7	0.2	**25**	19.7	23.0	5.4	5.2	**25**	15.3	17.6	7.5	0.0
26	7.3	0.0	4.7	4.0	**26**	17.6	20.9	6.9	0.0	**26**	20.2	24.1	5.7	0.6	**26**	15.1	15.3	6.1	0.0
27	7.4	0.0	4.5	5.0	**27**	19.0	22.0	5.9	0.0	**27**	19.7	24.2	6.0	0.2	**27**	17.1	19.7	6.9	0.0
28	7.1	0.0	4.4	5.2	**28**	22.8	24.6	5.1	0.0	**28**	18.2	22.6	6.9	0.0	**28**	19.8	20.4	4.8	0.0
29	7.5	0.0	4.8	7.2	**29**	17.6	21.4	7.2	0.0	**29**	20.6	24.8	5.7	0.0	**29**	24.7	26.6	4.9	0.0
30	13.1	14.1	7.6	3.4	**30**	14.1	15.1	6.5	0.0	**30**	17.9	21.4	6.9	0.0	**30**	15.5	18.2	7.8	0.0
31	14.6	16.5	7.5	0.0	**31**					**31**	12.9	13.6	8.0	0.4	**31**	12.1	12.0	7.8	0.8
Total	**338.0**	**294.4**	**159.7**	**62.8**	**Total**	**457.3**	**503.8**	**214.0**	**66.8**	**Total**	**583.2**	**684.3**	**196.1**	**34.6**	**Total**	**521.5**	**586.8**	**208.6**	**47.0**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z]Growing Degree Days calculated using a base temperature of 0° C; [y]Corn Heat Units; [x]Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w]Total daily amounts of precipitation

Table C.9. Daily accumulation of various heat units and daily precipitations at Swift Current, SK, 2005.

	May					June					July					**August**			
Day	*GDD*[z]	*CHU*[y]	*P-Days*[x]	*Prec*[w] *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	0.0	0.0	0.0	0.0	**1**	12.7	13.0	8.2	1.0	**1**	18.8	23.2	6.4	0.0	**1**	25.5	23.9	4.9	0.0
2	1.0	0.0	0.4	0.0	**2**	13.0	13.9	8.0	6.7	**2**	15.9	18.9	7.9	10.2	**2**	19.8	23.5	5.6	0.0
3	6.4	1.7	2.3	0.2	**3**	12.4	12.6	7.7	1.2	**3**	13.8	15.3	8.2	0.4	**3**	16.3	18.9	7.3	0.0
4	10.8	9.8	6.3	0.0	**4**	13.1	13.6	8.6	0.0	**4**	16.0	18.5	7.3	0.0	**4**	18.1	18.9	5.6	0.0
5	9.7	8.0	5.1	0.0	**5**	13.7	15.0	8.4	1.1	**5**	19.3	22.4	5.7	0.0	**5**	23.9	25.6	5.1	0.0
6	16.0	18.1	7.0	2.4	**6**	12.7	12.8	8.4	6.7	**6**	20.8	24.5	5.5	0.0	**6**	22.9	21.9	4.9	0.0
7	11.7	11.5	6.5	0.0	**7**	11.5	10.5	7.6	16.3	**7**	19.0	23.6	6.2	0.0	**7**	21.5	22.9	5.0	1.8
8	9.1	5.2	5.6	0.0	**8**	8.3	1.5	5.8	0.7	**8**	21.4	23.8	5.1	0.0	**8**	14.7	16.9	8.5	2.6
9	11.2	10.1	7.2	0.0	**9**	10.8	8.9	7.4	9.0	**9**	20.2	24.9	6.0	0.4	**9**	13.6	14.9	7.7	1.0
10	3.1	0.0	0.7	0.0	**10**	12.5	12.9	7.1	0.7	**10**	18.0	21.8	6.8	0.0	**10**	12.8	13.2	8.1	3.4
11	2.7	0.0	1.1	0.0	**11**	15.6	18.1	7.7	0.0	**11**	18.6	22.1	6.3	0.0	**11**	13.3	14.3	8.0	1.2
12	4.6	0.0	1.1	0.0	**12**	16.3	19.2	7.5	3.1	**12**	20.8	22.4	4.9	0.0	**12**	10.7	8.9	7.1	6.4
13	4.3	0.0	1.0	0.0	**13**	14.7	16.9	8.5	4.1	**13**	22.5	25.7	5.2	0.0	**13**	11.3	10.8	6.4	0.0
14	5.2	0.0	1.3	0.0	**14**	14.0	15.5	7.6	2.4	**14**	17.0	20.0	7.2	0.0	**14**	15.4	18.0	7.8	0.4
15	14.7	16.5	7.4	0.0	**15**	16.0	19.2	8.0	3.7	**15**	18.5	20.6	5.9	0.0	**15**	15.4	18.0	8.0	0.0
16	16.9	19.7	7.1	1.2	**16**	14.6	16.4	7.4	0.0	**16**	20.1	24.6	5.9	5.8	**16**	16.4	18.4	6.8	0.0
17	13.4	14.2	8.6	8.6	**17**	20.2	24.4	5.8	24.2	**17**	16.5	20.1	7.9	2.8	**17**	12.5	12.8	7.7	0.8
18	14.0	15.6	7.9	0.0	**18**	17.3	21.2	7.4	0.0	**18**	18.7	21.7	6.1	0.0	**18**	11.7	11.5	7.0	1.2
19	15.7	18.0	7.4	0.0	**19**	15.9	18.5	7.5	0.0	**19**	15.1	17.5	7.8	0.0	**19**	11.9	11.7	7.2	0.0
20	14.6	16.4	7.4	0.0	**20**	17.6	20.0	6.5	0.4	**20**	17.5	21.2	7.2	0.0	**20**	14.8	15.4	6.3	0.0
21	10.3	7.9	6.9	9.8	**21**	20.4	22.9	5.1	0.0	**21**	17.3	20.7	7.2	0.0	**21**	22.2	21.4	4.8	0.0
22	14.0	15.1	6.7	0.4	**22**	23.8	27.2	5.1	0.8	**22**	18.8	22.4	6.2	0.0	**22**	21.4	25.2	5.5	2.4
23	12.6	13.2	7.4	0.2	**23**	13.7	15.1	7.6	0.8	**23**	20.3	24.4	5.7	1.0	**23**	17.0	20.9	7.7	22.1
24	10.6	8.8	6.7	0.0	**24**	11.8	11.6	7.1	0.0	**24**	14.2	16.0	7.8	0.0	**24**	12.8	13.3	8.3	4.5
25	8.8	5.2	5.2	0.0	**25**	14.5	16.4	7.7	4.2	**25**	12.0	12.0	6.6	0.0	**25**	10.6	7.4	7.8	0.6
26	9.8	7.5	5.8	0.8	**26**	14.6	16.7	8.2	0.0	**26**	14.8	16.6	7.3	0.0	**26**	15.0	17.2	7.7	0.0
27	10.1	8.5	5.7	0.0	**27**	13.5	14.7	8.1	0.0	**27**	16.3	19.5	7.7	0.0	**27**	16.9	19.2	6.8	0.0
28	6.1	0.0	2.6	0.0	**28**	14.9	17.2	8.2	11.4	**28**	16.5	19.0	7.2	0.8	**28**	20.8	22.8	5.0	0.0
29	9.2	6.6	5.3	0.0	**29**	13.7	14.6	8.7	0.0	**29**	21.0	23.7	5.2	0.0	**29**	23.7	24.4	5.0	0.0
30	12.0	12.1	6.5	0.0	**30**	16.1	19.4	8.0	0.4	**30**	21.8	25.9	5.5	0.0	**30**	13.2	14.2	8.2	3.7
31	12.4	12.7	7.1	0.8	**31**					**31**	25.6	24.9	4.9	0.0	**31**	14.2	15.9	7.6	0.0
Total	**300.1**	**262.4**	**157.1**	**24.4**	**Total**	**439.0**	**479.8**	**224.9**	**98.9**	**Total**	**566.5**	**658.2**	**200.6**	**21.4**	**Total**	**509.5**	**542.6**	**209.0**	**52.1**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z]Growing Degree Days calculated using a base temperature of 0° C; [y]Corn Heat Units; [x]Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w]Total daily amounts of precipitation

Table C.10. Daily accumulation of various heat units and daily precipitations at Swift Current, SK, 2006

May					June					July					**August**				
Day	*GDD*[z]	*CHU*[y]	*P-Days*[x]	*Prec*[w] *(mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*	*Day*	*GDD*	*CHU*	*P-Days*	*Prec. (mm)*
1	4.5	0.0	1.25	1.3	**1**	17.7	19.7	6.35	0.0	**1**	18.4	22.5	6.65	0.4	**1**	18.3	19.3	5.6	0.0
2	2.3	0.0	0.00	1.0	**2**	23.2	24.2	5.06	0.0	**2**	19.2	22.9	5.91	0.0	**2**	16.8	19.3	7.0	0.4
3	0.3	0.0	0.00	0.2	**3**	19.4	23.4	5.83	0.8	**3**	16.9	19.4	6.93	0.0	**3**	18.0	20.8	6.5	0.6
4	4.8	0.0	1.36	0.0	**4**	18.1	20.8	6.37	0.0	**4**	20.3	23.4	5.36	0.0	**4**	18.9	21.4	5.8	0.0
5	12.3	12.5	6.40	0.0	**5**	17.8	21.6	6.96	0.0	**5**	22.3	25.3	5.17	0.0	**5**	16.3	19.2	7.5	0.0
6	14.9	16.6	7.19	0.0	**6**	16.5	19.6	7.54	0.0	**6**	23.8	27.8	5.01	0.0	**6**	17.0	18.5	6.3	0.0
7	11.1	10.3	6.50	1.0	**7**	14.1	15.5	7.13	0.0	**7**	21.0	24.1	5.33	0.0	**7**	25.7	25.1	4.8	0.0
8	10.1	8.5	5.80	3.6	**8**	12.0	11.5	7.89	29.0	**8**	18.6	22.1	6.36	0.0	**8**	25.2	25.1	4.9	0.0
9	4.5	0.0	1.18	1.2	**9**	11.2	9.6	7.69	2.6	**9**	19.5	20.8	5.02	0.0	**9**	24.6	26.8	5.0	2.0
10	4.6	0.0	1.27	0.4	**10**	10.0	6.2	7.23	9.8	**10**	23.3	25.2	5.10	4.2	**10**	21.3	25.9	5.7	1.8
11	8.1	4.7	3.76	0.0	**11**	11.5	10.6	7.65	0.4	**11**	21.7	23.8	5.08	0.0	**11**	19.2	23.7	6.2	6.0
12	12.8	13.5	7.31	1.4	**12**	12.4	12.8	7.26	0.0	**12**	23.0	24.7	5.10	5.8	**12**	14.1	15.8	8.3	0.0
13	10.6	9.4	6.08	0.2	**13**	14.7	16.5	7.31	0.0	**13**	21.4	25.9	5.64	4.8	**13**	15.7	17.8	7.2	0.0
14	11.5	11.1	6.11	0.0	**14**	15.5	18.3	8.38	7.8	**14**	22.1	25.3	5.21	0.0	**14**	18.4	19.7	5.7	0.0
15	15.4	16.8	6.63	0.0	**15**	15.8	18.7	7.87	1.8	**15**	23.3	25.0	5.09	0.0	**15**	20.7	23.4	5.2	0.0
16	21.4	22.8	4.96	0.0	**16**	13.8	15.2	8.37	3.8	**16**	19.0	23.0	6.09	0.0	**16**	17.3	21.1	7.3	0.4
17	19.3	19.6	4.95	0.0	**17**	15.4	18.1	8.05	0.8	**17**	19.4	19.5	4.91	0.0	**17**	15.8	18.3	7.5	0.0
18	21.4	24.9	5.38	0.0	**18**	16.2	19.4	7.80	0.0	**18**	20.0	24.6	5.97	0.0	**18**	17.2	19.4	6.6	0.0
19	18.8	22.0	6.11	0.4	**19**	15.8	18.2	7.34	15.0	**19**	17.8	20.6	6.60	0.0	**19**	21.3	23.0	5.0	0.0
20	14.7	16.8	7.79	1.0	**20**	13.9	15.3	8.55	7.8	**20**	16.9	20.4	7.54	0.4	**20**	16.6	19.3	7.2	0.0
21	18.3	20.5	6.06	0.0	**21**	14.8	17.1	8.04	0.0	**21**	20.3	21.5	4.71	0.0	**21**	19.4	20.3	5.0	0.0
22	23.7	23.9	5.02	0.0	**22**	14.8	17.0	7.82	6.4	**22**	24.0	25.5	5.05	0.0	**22**	24.9	26.8	4.9	0.0
23	18.6	23.5	6.51	7.2	**23**	15.6	18.1	7.60	0.4	**23**	26.7	26.9	4.54	6.0	**23**	22.0	25.0	5.2	0.0
24	15.1	17.5	7.79	4.8	**24**	15.6	18.1	7.58	0.0	**24**	24.4	28.1	4.91	2.6	**24**	15.8	18.7	7.9	0.0
25	15.1	16.9	7.03	0.2	**25**	17.5	20.3	6.76	0.0	**25**	21.9	26.1	5.47	0.0	**25**	16.9	19.2	6.8	0.0
26	12.9	13.4	8.32	3.8	**26**	17.9	21.5	6.88	0.0	**26**	22.3	26.5	5.41	5.8	**26**	17.7	19.2	6.1	0.0
27	9.3	5.1	6.41	1.4	**27**	19.9	23.4	5.57	0.0	**27**	22.8	27.9	5.42	0.0	**27**	20.3	23.5	5.4	0.0
28	7.9	1.2	4.98	2.2	**28**	23.0	25.8	5.14	0.0	**28**	19.9	24.7	6.06	0.0	**28**	20.9	21.7	4.8	0.0
29	7.7	0.3	5.06	3.6	**29**	22.4	27.1	5.44	0.0	**29**	23.6	25.0	5.07	0.2	**29**	25.5	27.1	4.8	0.0
30	13.7	15.1	7.50	0.0	**30**	19.2	23.8	6.07	10.4	**30**	22.2	26.9	5.50	0.8	**30**	18.9	22.3	6.1	0.4
31	15.6	17.7	7.28	0.0	**31**					**31**	16.3	19.0	7.32	0.0	**31**	12.4	12.6	7.9	9.0
Total	**380.6**	**364.7**	**162.0**	**34.9**	**Total**	**485.0**	**547.4**	**213.5**	**96.8**	**Total**	**651.5**	**744.6**	**173.5**	**31.0**	**Total**	**592.3**	**659.3**	**190.1**	**20.6**

Data are based on Environment Canada's online climate data [October 4, 2007]; M – missing; T – trace precipitation

[z]Growing Degree Days calculated using a base temperature of 0° C; [y]Corn Heat Units; [x]Physiological days calculated using 5, 17, and 30° C as the minimum, optimum, and maximum temperatures, respectively; [w]Total daily amounts of precipitation

APPENDIX D – SCATTER PLOTS ILLUSTRATING THE RELATIONSHIP BETWEEN CANOLA YIELD AND NORMALIZED DIFFERENCE VEGETATION INDEX FOR INDIVIDUAL SITE-YEARS AND SENSING DATES

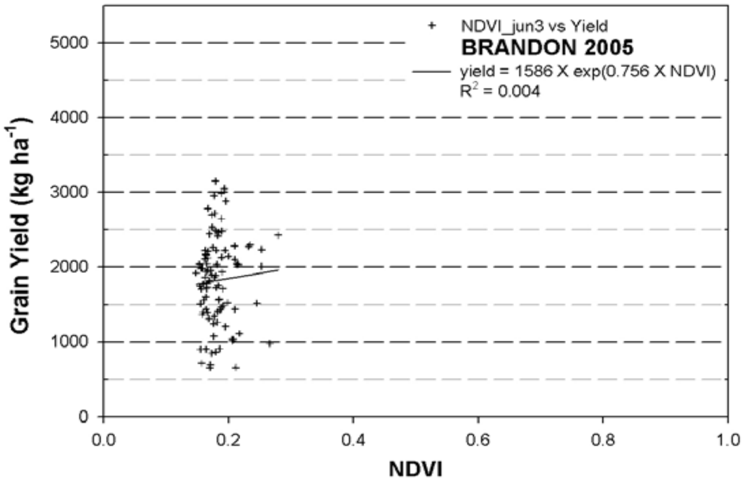

Figure D-1. Canola yield versus NDVI on June 3, 2005 at Brandon, MB when the crop was at growth stage 1 – 2.1 (Harper and Berkenkamp 1975).

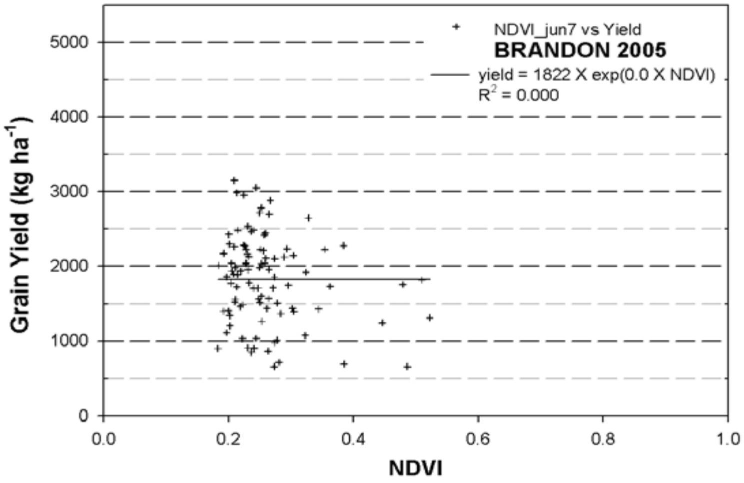

Figure D-2. Canola yield versus NDVI on June 7, 2005 at Brandon, MB when the crop was at growth stage 2.2 (Harper and Berkenkamp 1975).

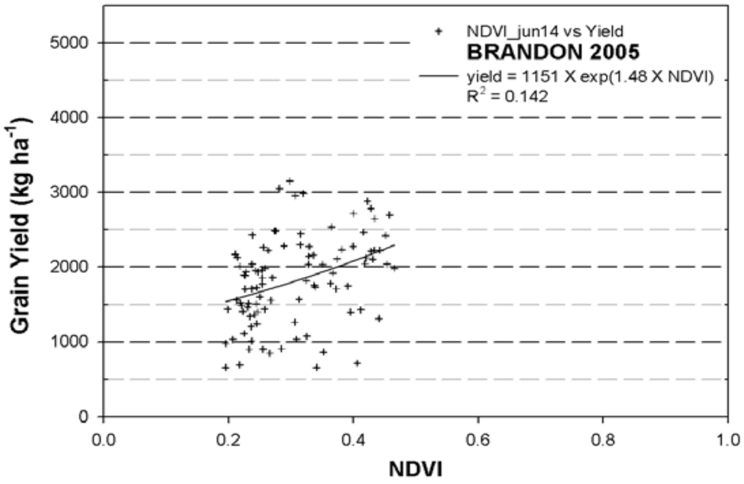

Figure D-3. Canola yield versus NDVI on June 14, 2005 at Brandon, MB when the crop was at growth stage 2.3 (Harper and Berkenkamp 1975).

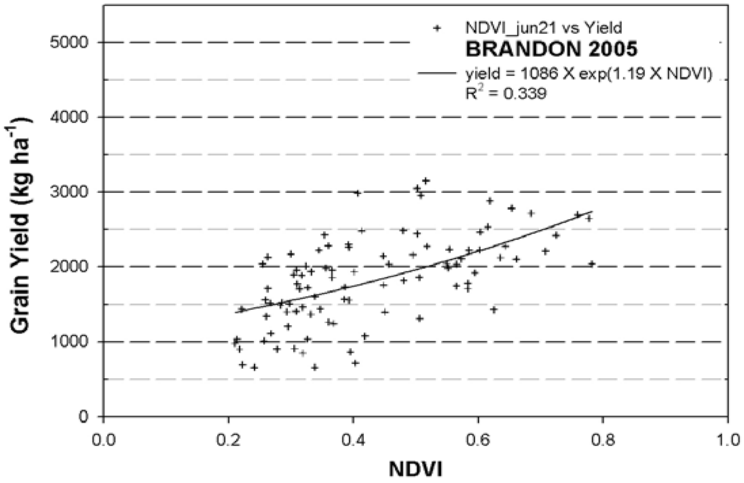

Figure D-4. Canola yield versus NDVI on June 21, 2005 at Brandon, MB when the crop was at growth stage 2.4 (Harper and Berkenkamp 1975).

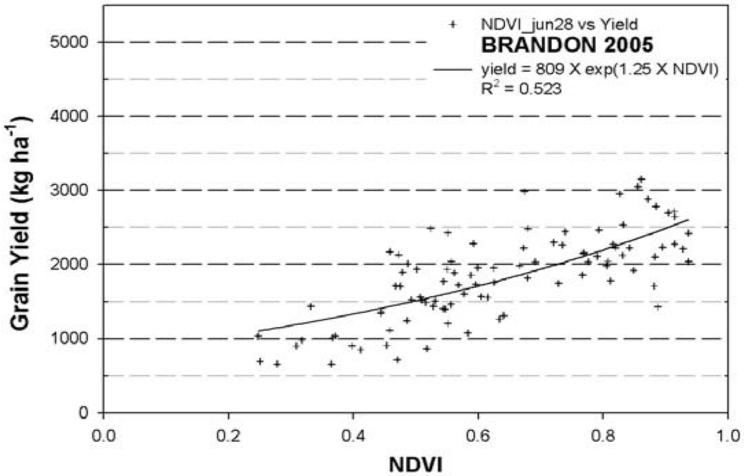

Figure D-5. Canola yield versus NDVI on June 28, 2005 at Brandon, MB when the crop was at growth stage 3.2 (Harper and Berkenkamp 1975).

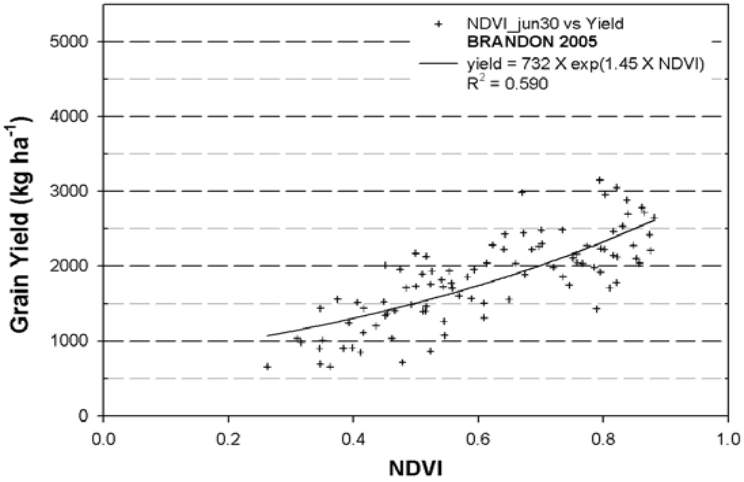

Figure D-6. Canola yield versus NDVI on June 30, 2005 at Brandon, MB when the crop was at growth stage 3.3 (Harper and Berkenkamp 1975).

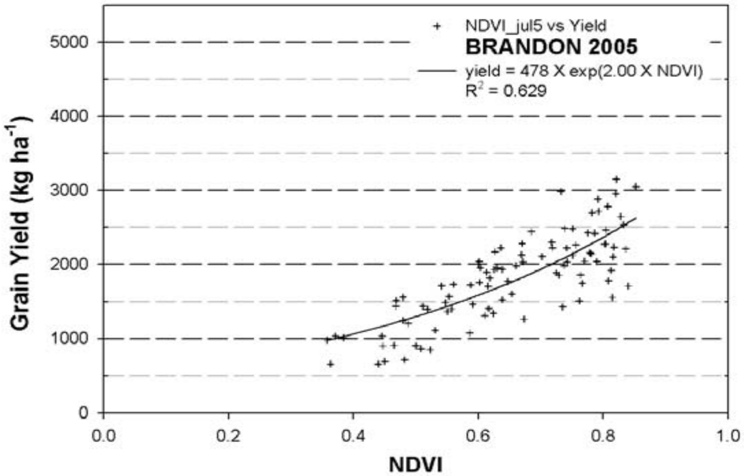

Figure D-7. Canola yield versus NDVI on July 5, 2005 at Brandon, MB when the crop was at growth stage 4.2 (Harper and Berkenkamp 1975).

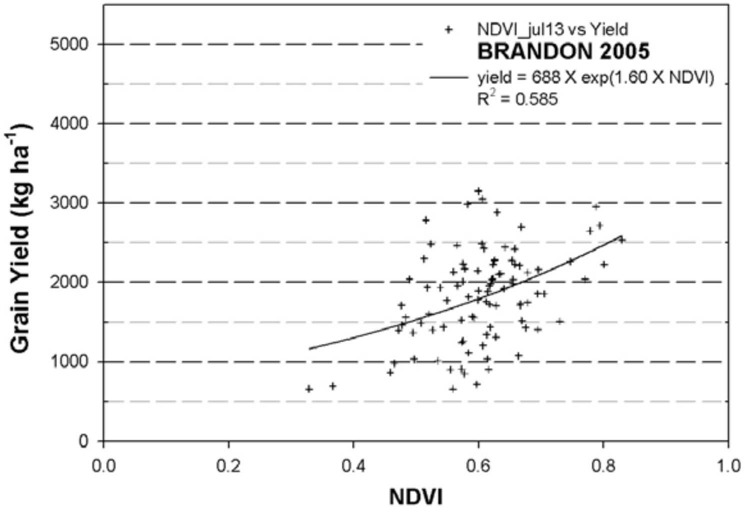

Figure D-8. Canola yield versus NDVI on July 13, 2005 at Brandon, MB when the crop was at growth stage 5.1 (Harper and Berkenkamp 1975).

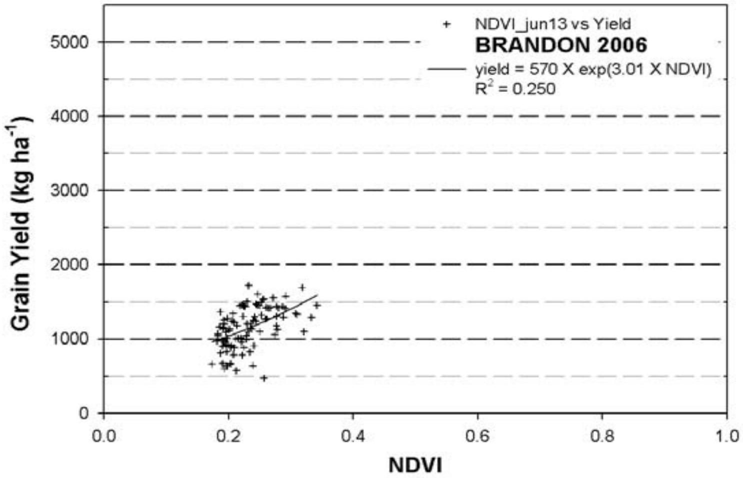

Figure D-9. Canola yield versus NDVI on June 13, 2006 at Brandon, MB when the crop was at growth stage 2.1 – 2.2 (Harper and Berkenkamp 1975).

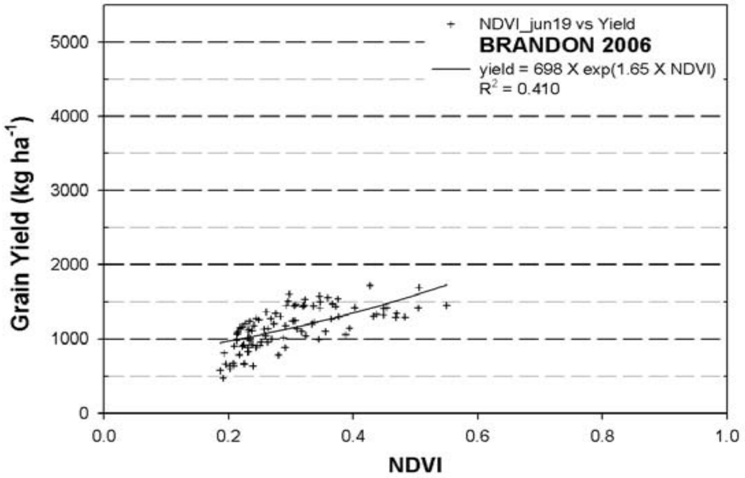

Figure D-11. Canola yield versus NDVI on June 19, 2006 at Brandon, MB when the crop was at growth stage 2.4 (Harper and Berkenkamp 1975).

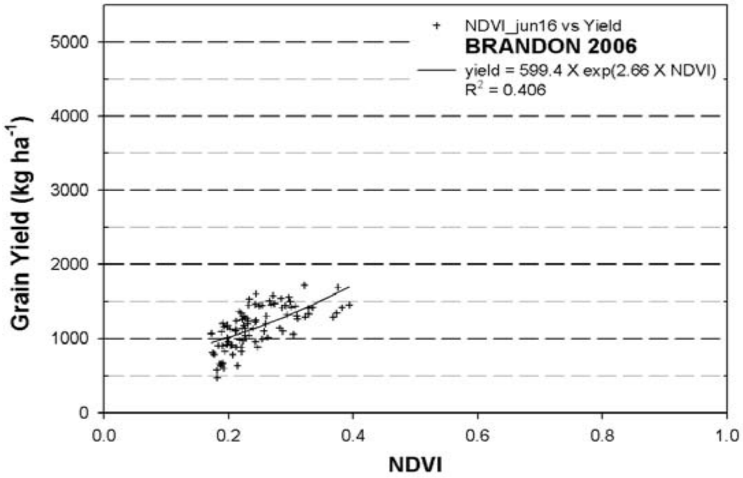

Figure D-10. Canola yield versus NDVI on June 16, 2006 at Brandon, MB when the crop was at growth stage 2.3 (Harper and Berkenkamp 1975).

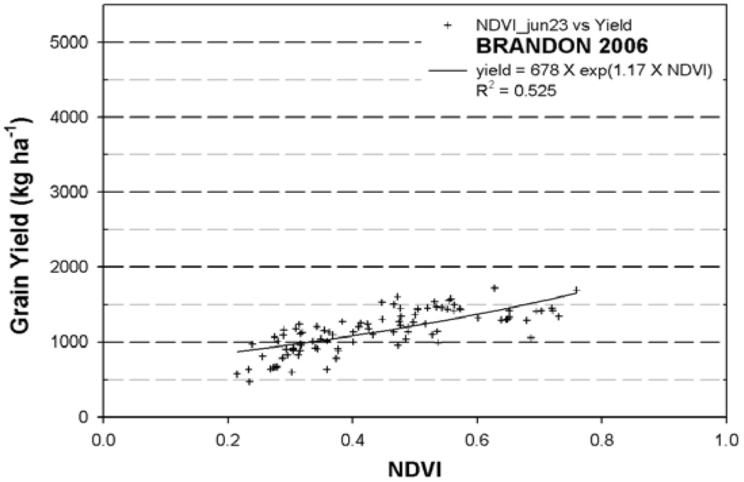

Figure D-12. Canola yield versus NDVI on June 23, 2006 at Brandon, MB when the crop was at growth stage 3.2 (Harper and Berkenkamp 1975).

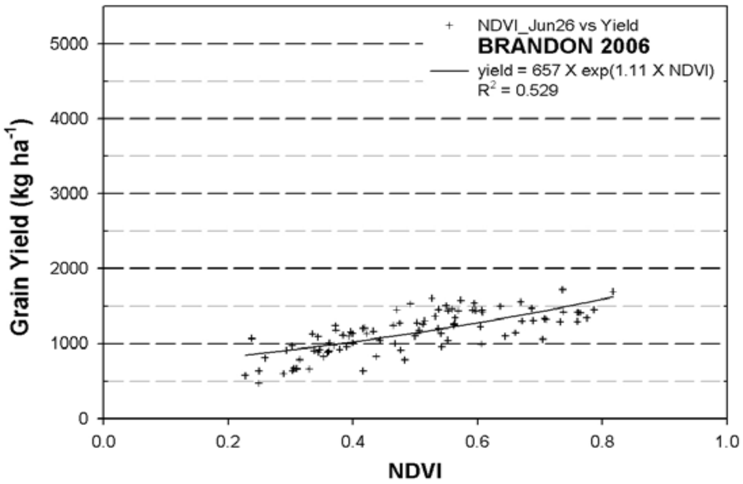

Figure D-13. Canola yield versus NDVI on June 26, 2006 at Brandon, MB when the crop was at growth stage 3.3 (Harper and Berkenkamp 1975).

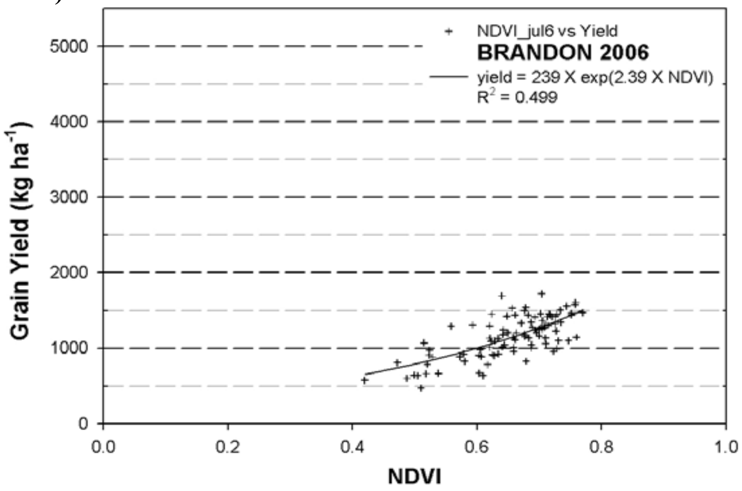

Figure D-14. Canola yield versus NDVI on July 6, 2006 at Brandon, MB when the crop was at growth stage 4.2 (Harper and Berkenkamp 1975).

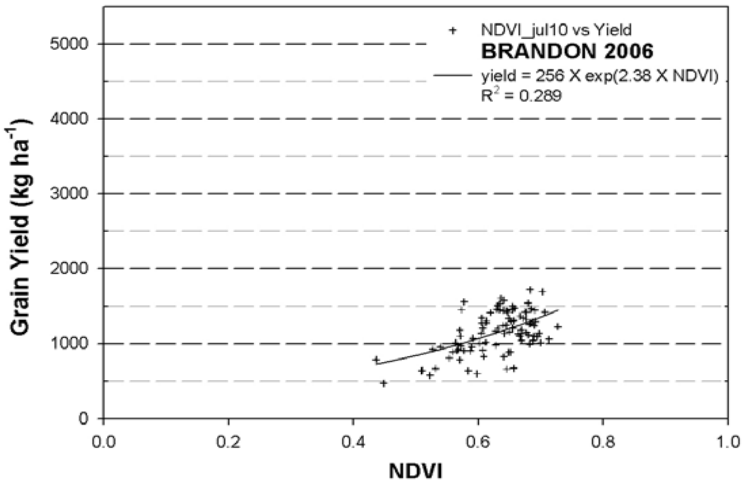

Figure D-15. Canola yield versus NDVI on July 10, 2006 at Brandon, MB when the crop was at growth stage 4.3 (Harper and Berkenkamp 1975).

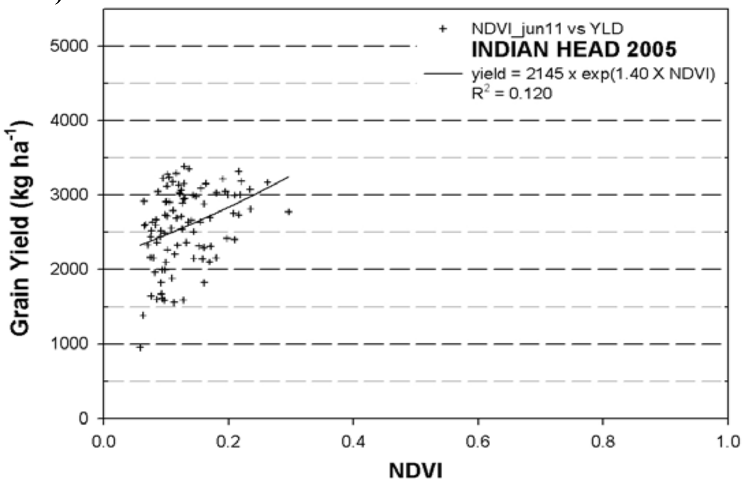

Figure D-16. Canola yield versus NDVI on June 13, 2005 at Indian Head, SK when the crop was at growth stages 1 – 2.1 (Harper and Berkenkamp 1975).

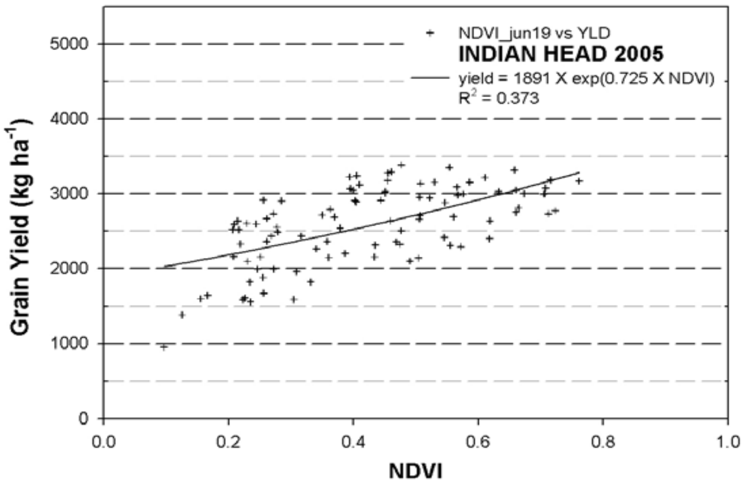

Figure D-17. Canola yield versus NDVI on June 19, 2005 at Indian Head, SK when the crop was at growth stages 2.4 – 2.6 (Harper and Berkenkamp 1975).

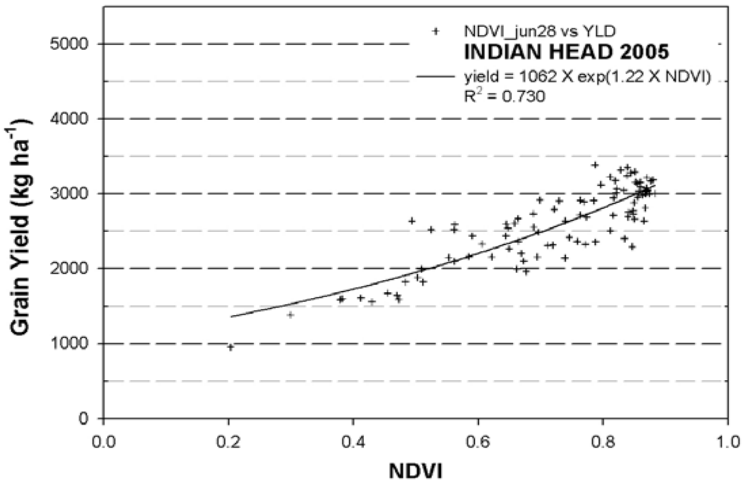

Figure D-19. Canola yield versus NDVI on June 28, 2005 at Indian Head, SK when the crop was at growth stages 3.3 – 4.1 (Harper and Berkenkamp 1975).

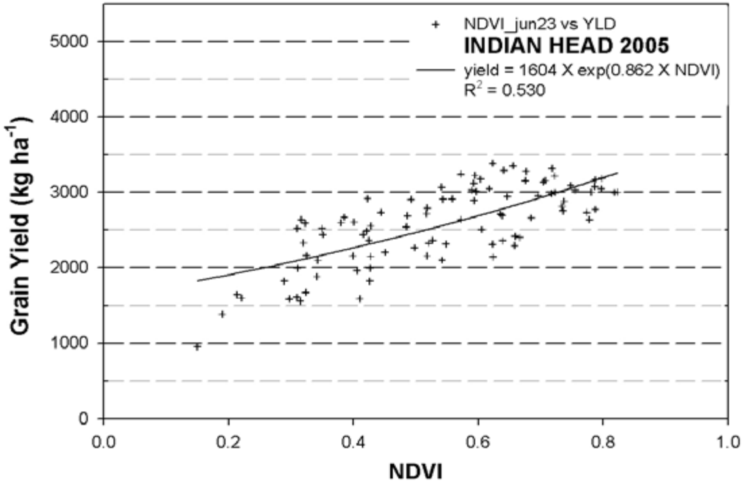

Figure D-18. Canola yield versus NDVI on June 23, 2005 at Indian Head, SK when the crop was at growth stages 3.1 – 3.2 (Harper and Berkenkamp 1975).

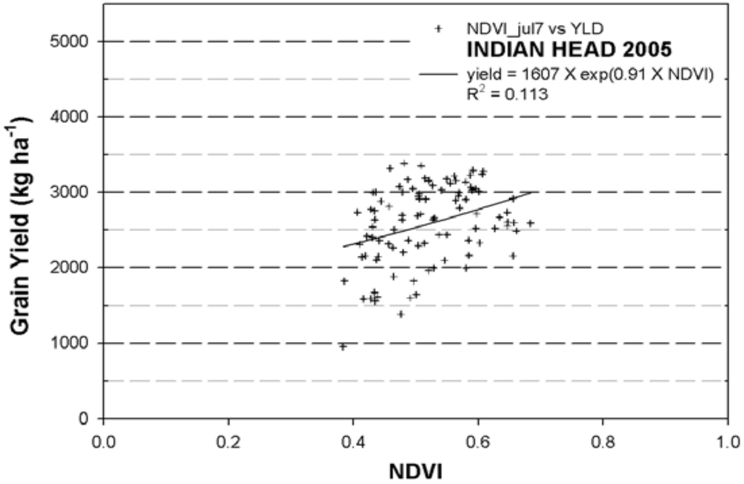

Figure D-20. Canola yield versus NDVI on July 7, 2005 at Indian Head, SK when the crop at growth stages 4.3 – 4.4 (Harper and Berkenkamp 1975).

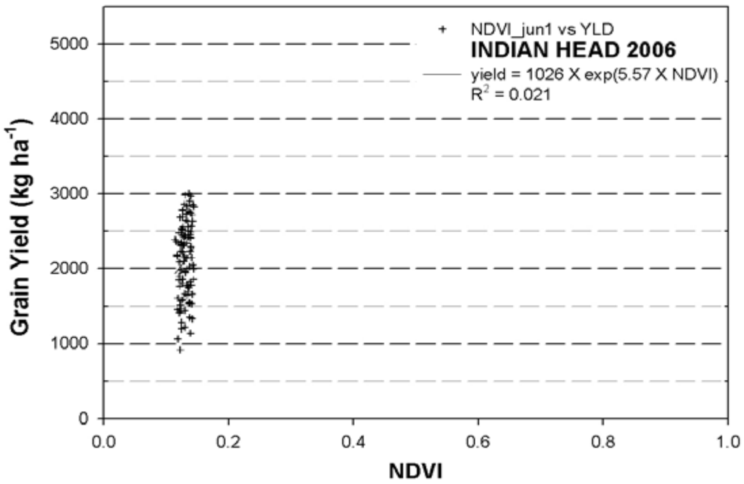

Figure D-21. Canola yield versus NDVI on June 1, 2006 at Indian Head, SK when the crop was at growth stages 1 – 2.1 (Harper and Berkenkamp 1975).

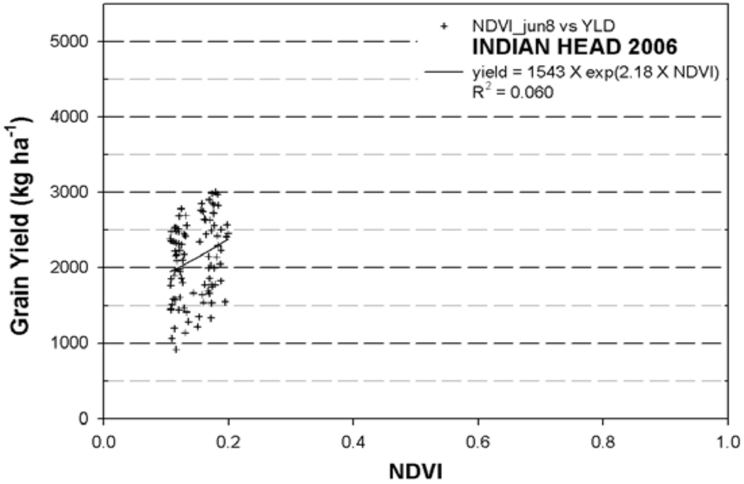

Figure D-22. Canola yield versus NDVI on June 8, 2006 at Indian Head, SK when the crop was at growth stages 2.2 – 2.3 (Harper and Berkenkamp 1975).

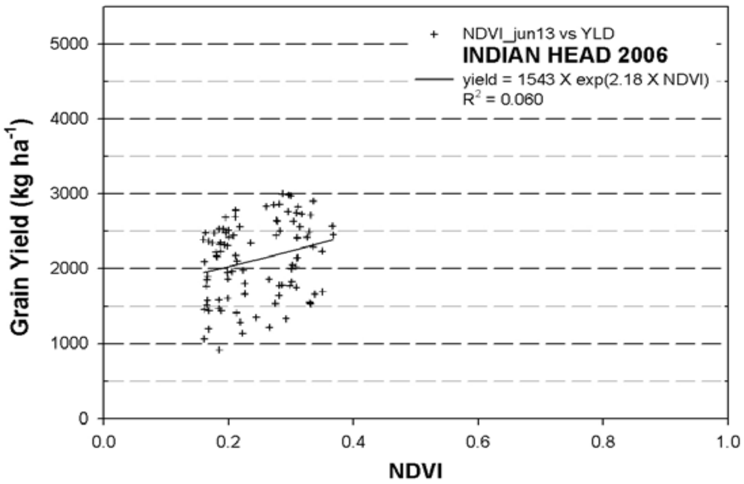

Figure D-23. Canola yield versus NDVI on June 13, 2006 at Indian Head, SK when the crop was at growth stages 2.3 – 2.4 (Harper and Berkenkamp 1975).

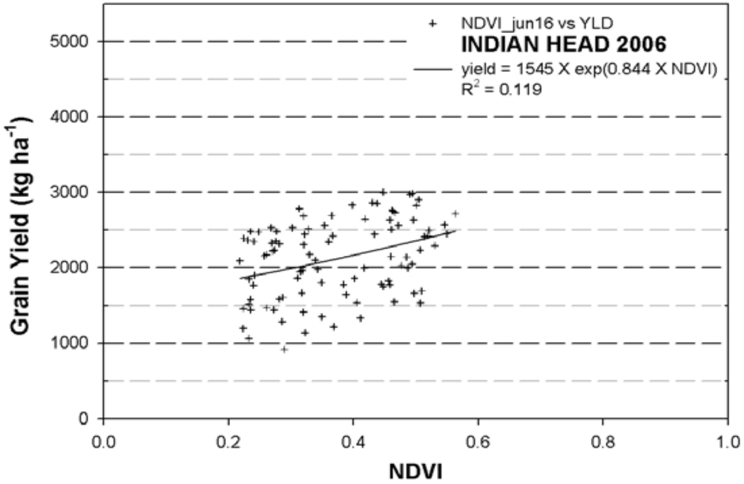

Figure D-24. Canola yield versus NDVI on June 16, 2006 at Indian Head, SK when the crop was at growth stages 2.4 – 2.5 (Harper and Berkenkamp 1975).

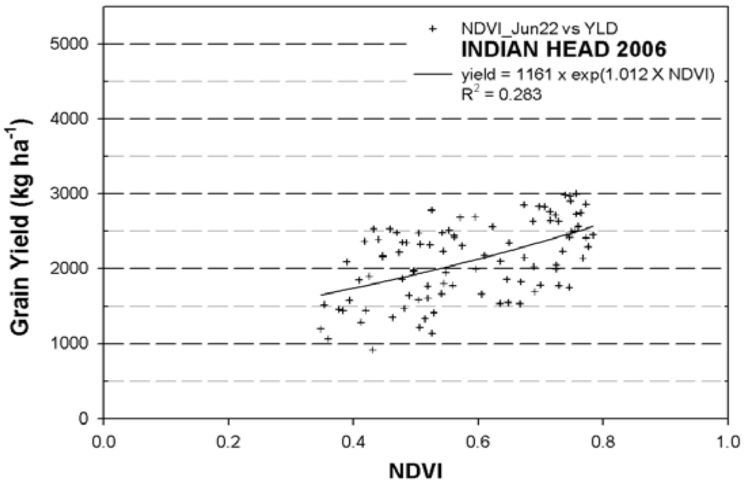

Figure D-25. Canola yield versus NDVI on June 22, 2006 at Indian Head, SK when the crop was at growth stages 2.6 – 3.1 (Harper and Berkenkamp 1975).

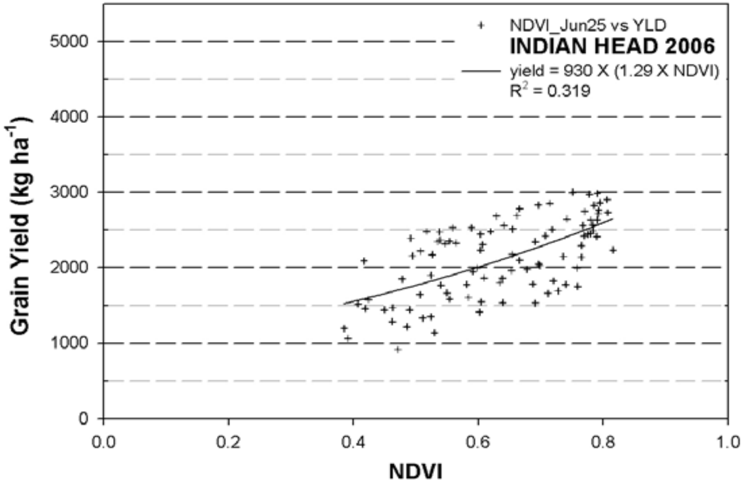

Figure D-26. Canola yield versus NDVI on June 25, 2006 at Indian Head, SK when the crop was at growth stages 3.1 – 3.2 (Harper and Berkenkamp 1975).

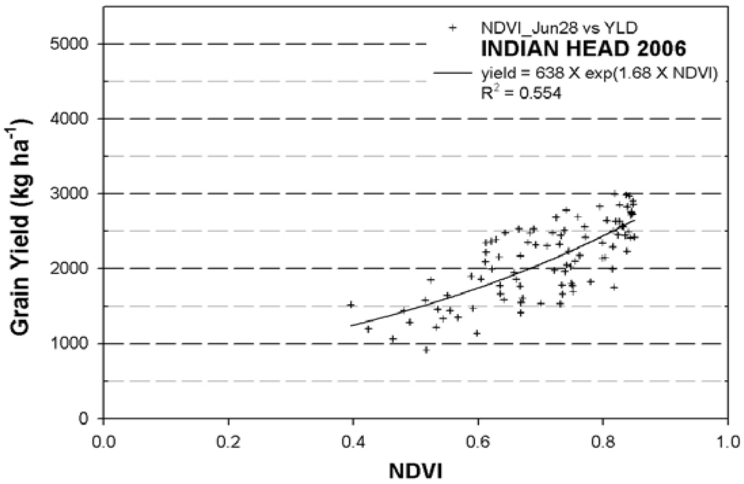

Figure D-27. Canola yield versus NDVI on June 28, 2006 at Indian Head, SK when the crop was at growth stages 3.3 – 4.1 (Harper and Berkenkamp 1975).

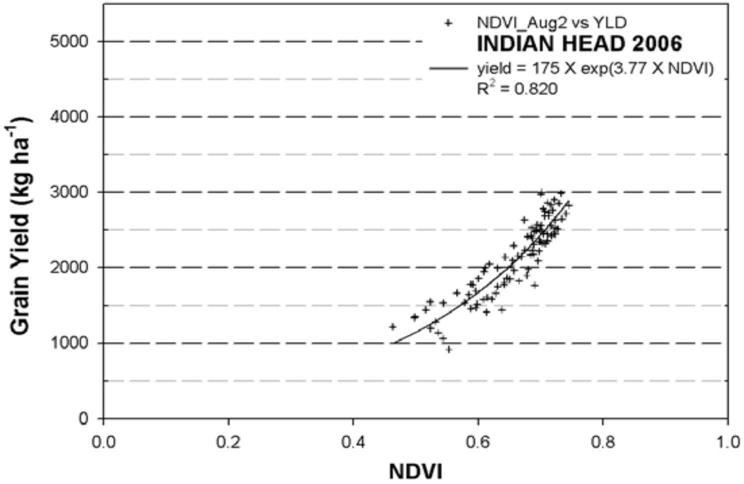

Figure D-28. Canola yield versus NDVI on June 1, 2006 at Indian Head, SK when the crop was at growth stage 5.3 (Harper and Berkenkamp 1975).

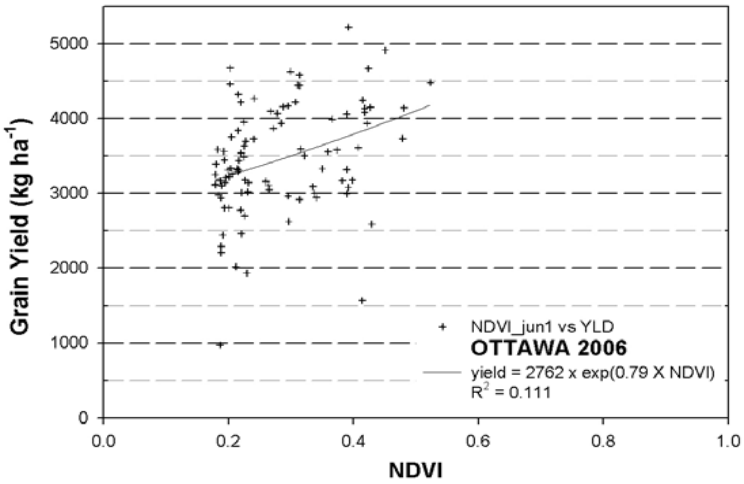

Figure D-29. Canola yield versus NDVI on June 1, 2005 at Ottawa, ON when the crop was at growth stage 2.1 (Harper and Berkenkamp 1975).

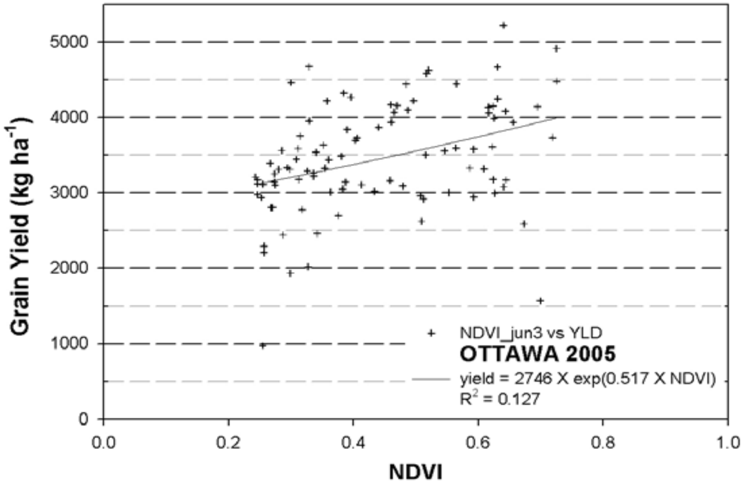

Figure D-30. Canola yield versus NDVI on June 3, 2005 at Ottawa, ON when the crop was at growth stages 2.1 -2.2 (Harper and Berkenkamp 1975).

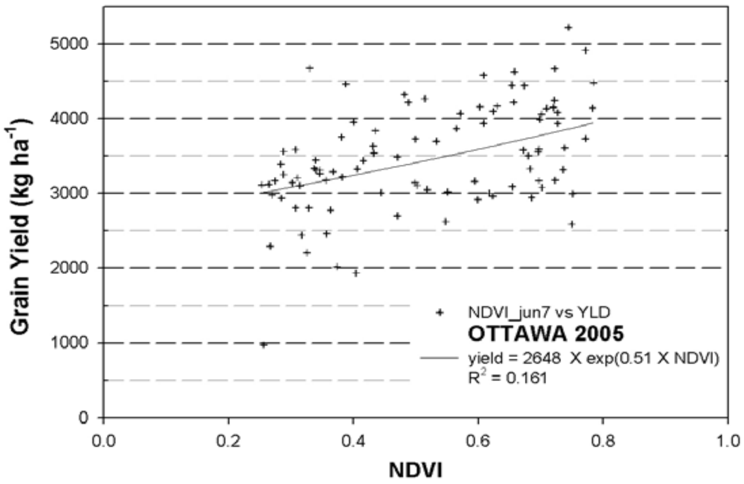

Figure D-31. Canola yield versus NDVI on June 7, 2005 at Ottawa, ON when the crop was at growth stages 2.4 – 2.5 (Harper and Berkenkamp 1975).

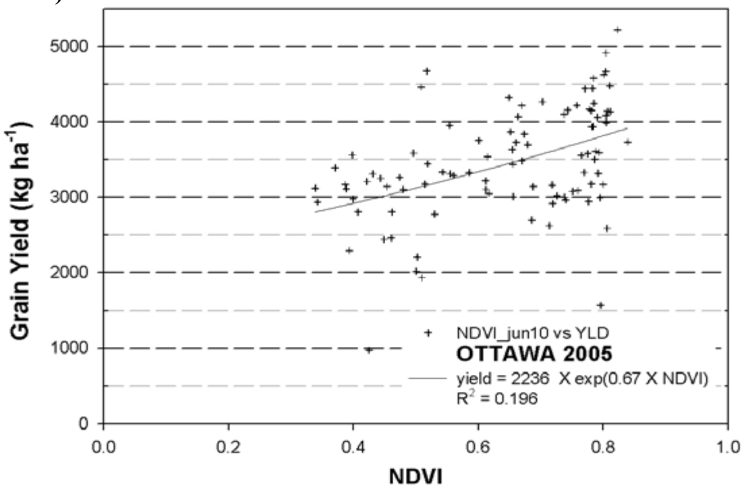

Figure D-32. Canola yield versus NDVI on June 10, 2005 at Ottawa, ON when the crop was at growth stages 2.5 – 2.7 (Harper and Berkenkamp 1975).

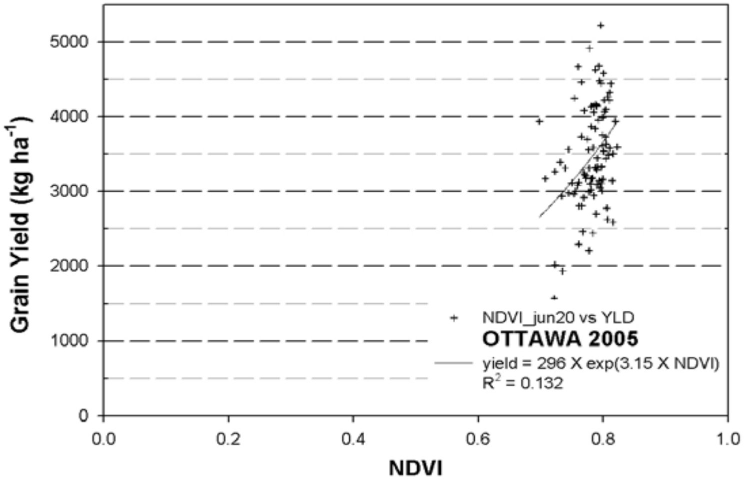

Figure D-33. Canola yield versus NDVI on June 20, 2005 at Ottawa, ON when the crop was at growth stage 4.2 (Harper and Berkenkamp 1975).

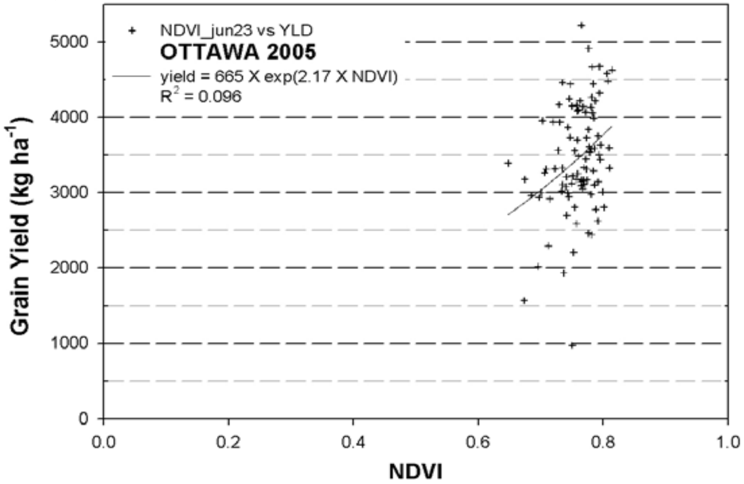

Figure D-34. Canola yield versus NDVI on June 23, 2005 at Ottawa, ON when the crop was at growth stage 4.3 (Harper and Berkenkamp 1975).

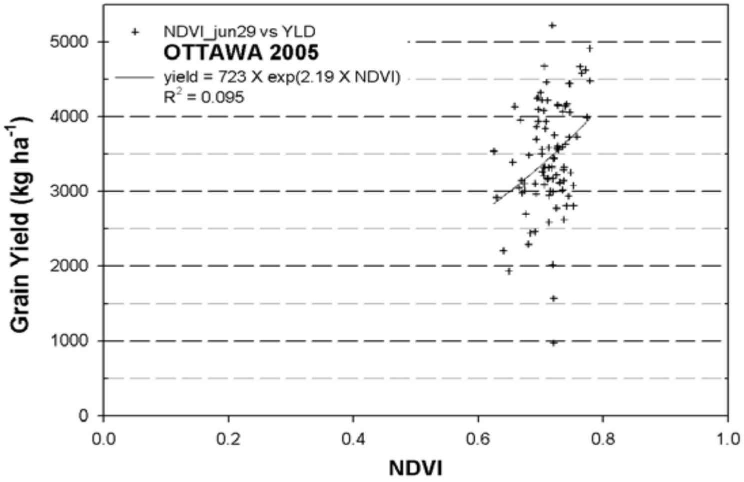

Figure D-35. Canola yield versus NDVI on June 29, 2005 at Ottawa, ON when the crop was at growth stage 5.2 (Harper and Berkenkamp 1975).

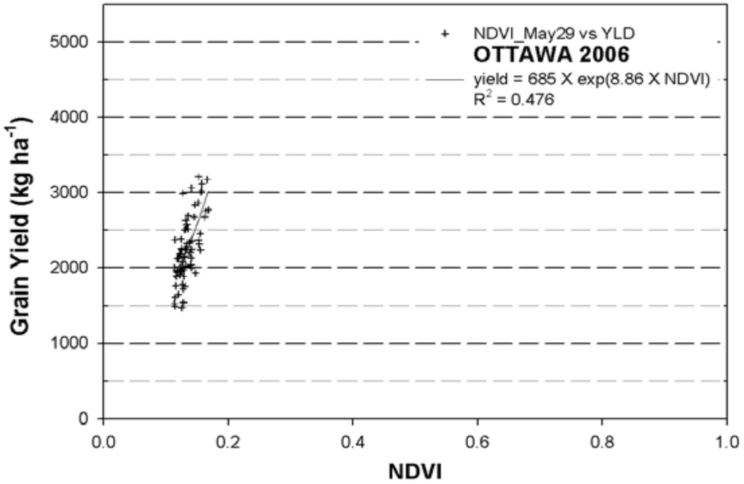

Figure D-36. Canola yield versus NDVI on May 29, 2006 at Ottawa, ON when the crop was at growth stages 2.1 – 2.2 (Harper and Berkenkamp 1975).

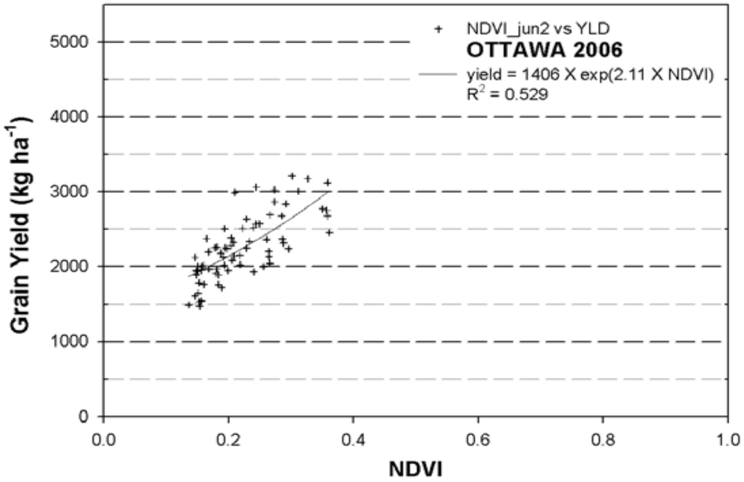

Figure D-37. Canola yield versus NDVI on June 2, 2006 at Ottawa, ON when the crop was at growth stage 2.3 (Harper and Berkenkamp 1975).

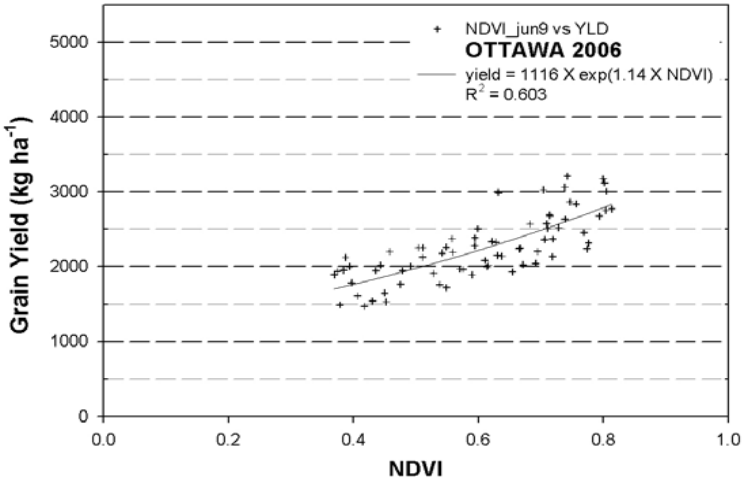

Figure D-39. Canola yield versus NDVI on June 9, 2006 at Ottawa, ON when the crop was growth stage 2.5 (Harper and Berkenkamp 1975).

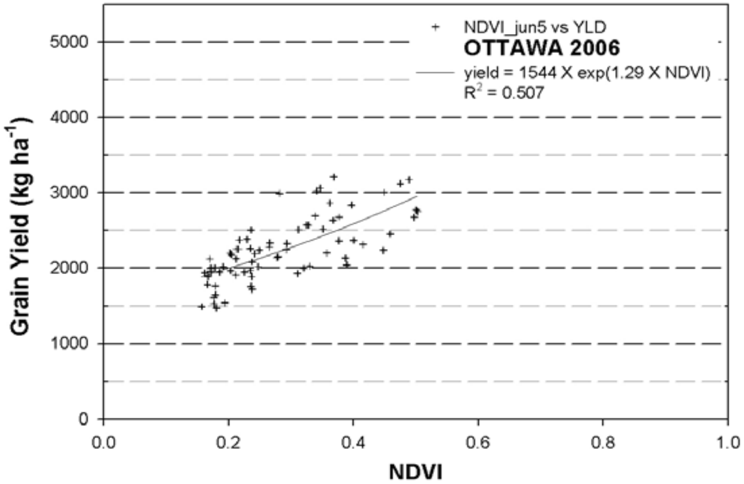

Figure D-38. Canola yield versus NDVI on June 5, 2006 at Ottawa, ON when the crop was at growth stage 2.4 (Harper and Berkenkamp 1975).

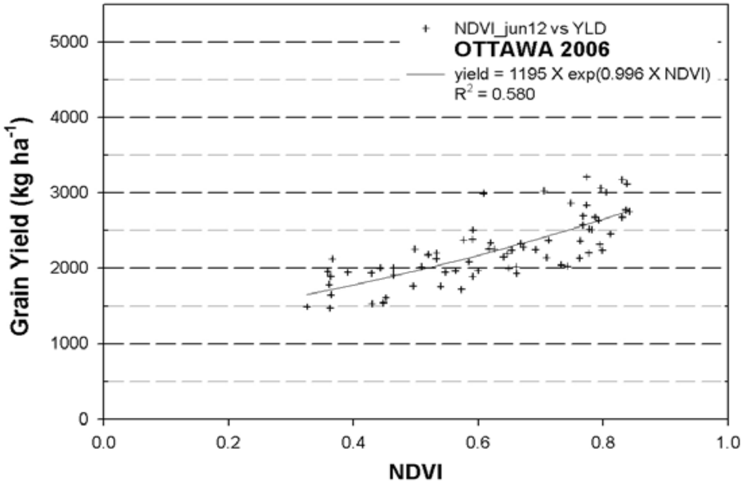

Figure D-40. Canola yield versus NDVI on June 12, 2006 at Ottawa, ON when the crop was at growth stage 2.6 (Harper and Berkenkamp 1975).

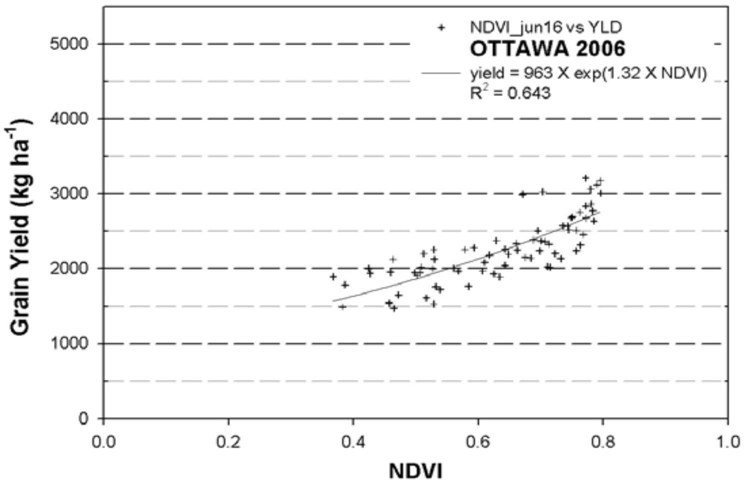

Figure D-41. Canola yield versus NDVI on June 16, 2006 at Ottawa, ON when the crop was at growth stage 2.7 (Harper and Berkenkamp 1975).

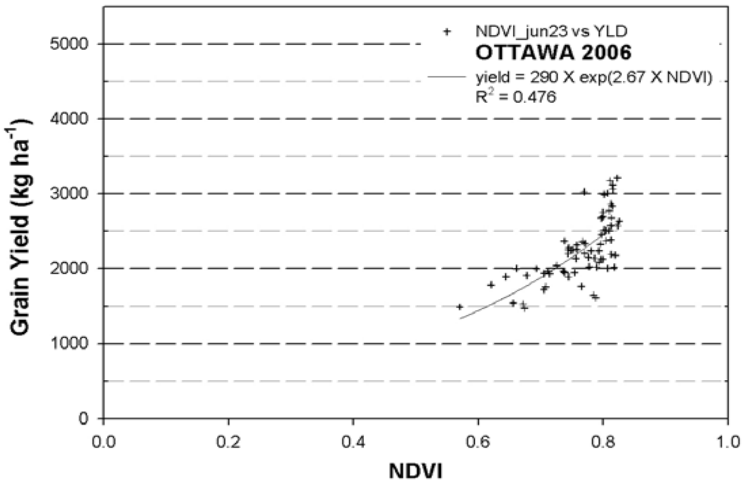

Figure D-43. Canola yield versus NDVI on June 23, 2006 at Ottawa, ON when the crop was at growth stages 3.3 – 4.1 (Harper and Berkenkamp 1975).

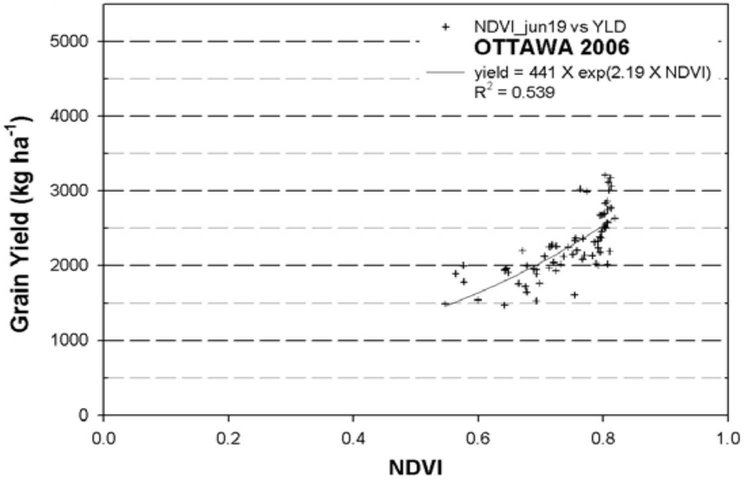

Figure D-42. Canola yield versus NDVI on June 19, 2006 at Ottawa, ON when the crop was at growth stages 3.1 – 3.2 (Harper and Berkenkamp 1975).

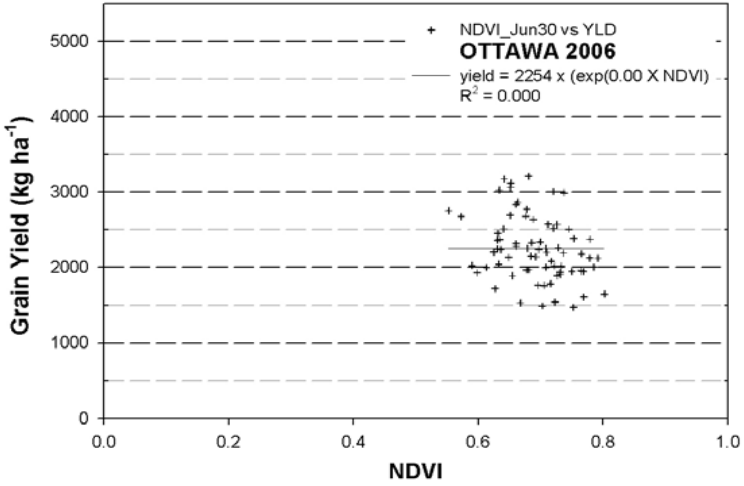

Figure D-44. Canola yield versus NDVI on June 30, 2006 at Ottawa, ON when the crop was at the growth stages 4.2 – 4.3 (Harper and Berkenkamp 1975).

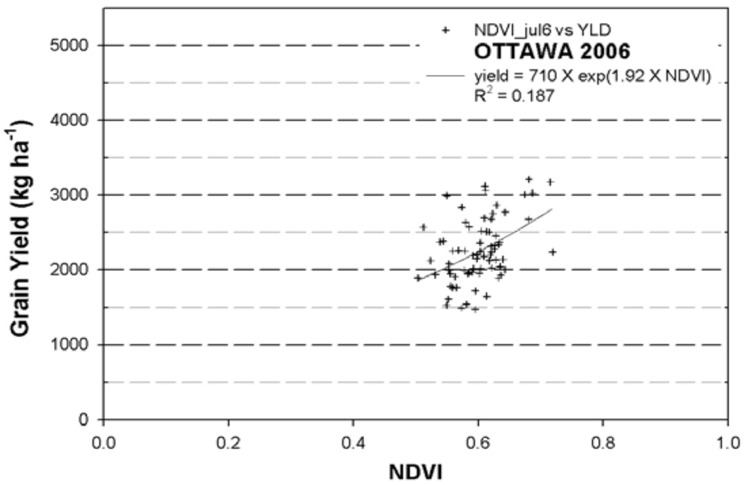

Figure D-45. Canola yield versus NDVI on July 6, 2006 at Ottawa, ON when the crop was at growth stages 4.4 – 5.1 (Harper and Berkenkamp 1975).

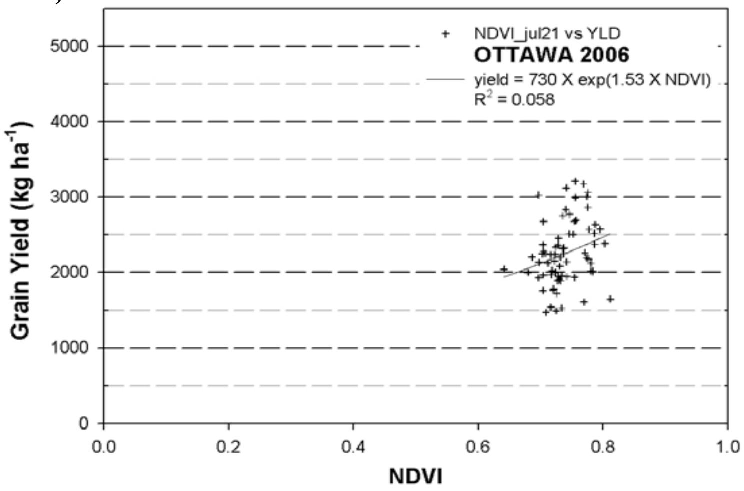

Figure D-46. Canola yield versus NDVI on July 21, 2005 at Ottawa, ON when the crop was at the growth stages 5.2 – 5.3 (Harper and Berkenkamp 1975).

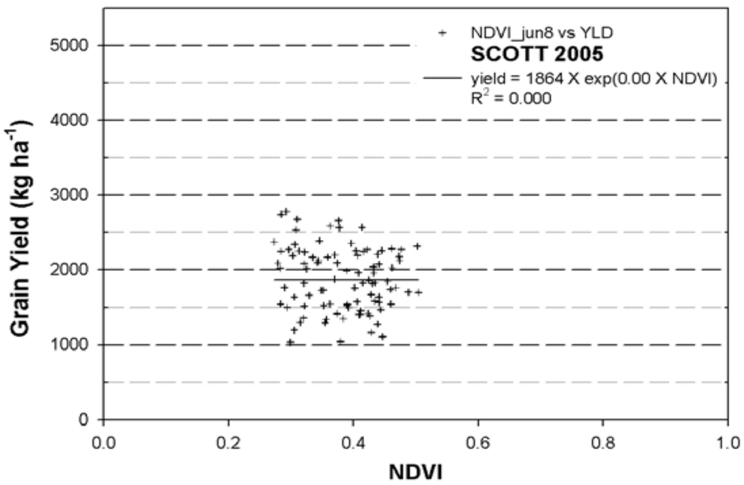

Figure D-47. Canola yield versus NDVI on June 8, 2005 at Scott, SK when the crop was at growth stages 2.1 – 2.2 (Harper and Berkenkamp 1975).

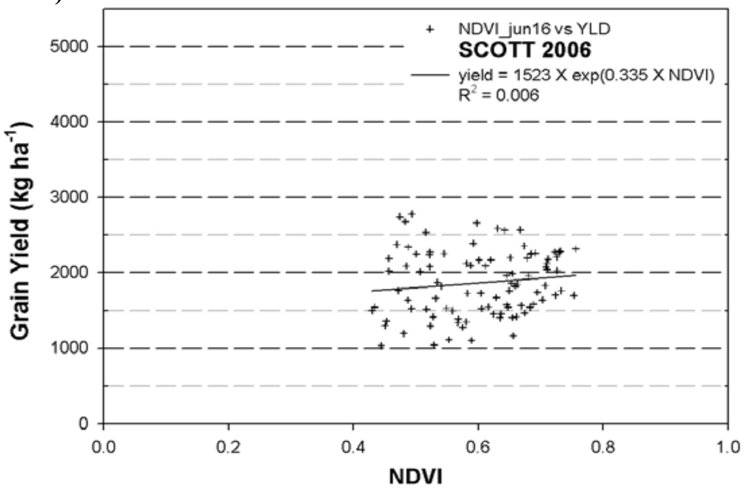

Figure D-48. Canola yield versus NDVI on June 16, 2005 at Scott, SK when the crop was at growth stage 2.3 (Harper and Berkenkamp 1975).

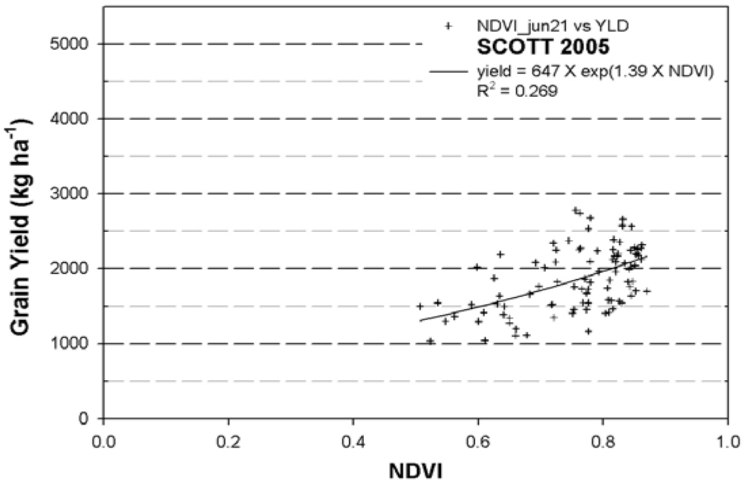

Figure D-49. Canola yield versus NDVI on June 21, 2005 at Scott, SK when the crop was at growth stage 2.4 (Harper and Berkenkamp 1975).

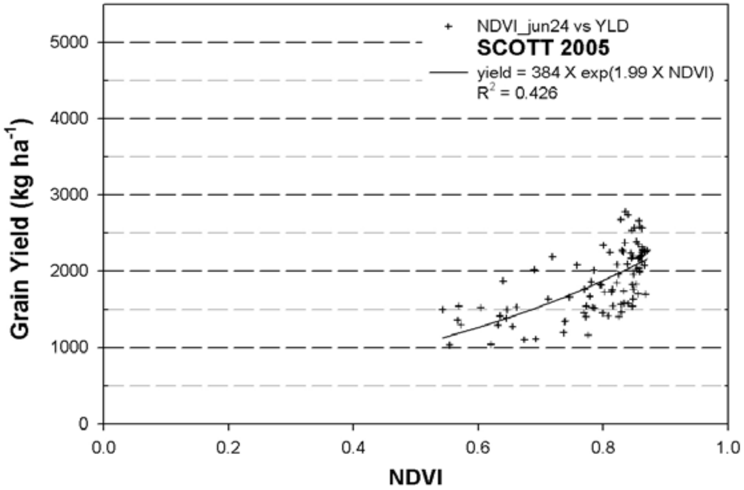

Figure D-50. Canola yield versus NDVI on June 24, 2005 at Scott, SK when the crop was at growth stages 2.5 – 2.6 (Harper and Berkenkamp 1975).

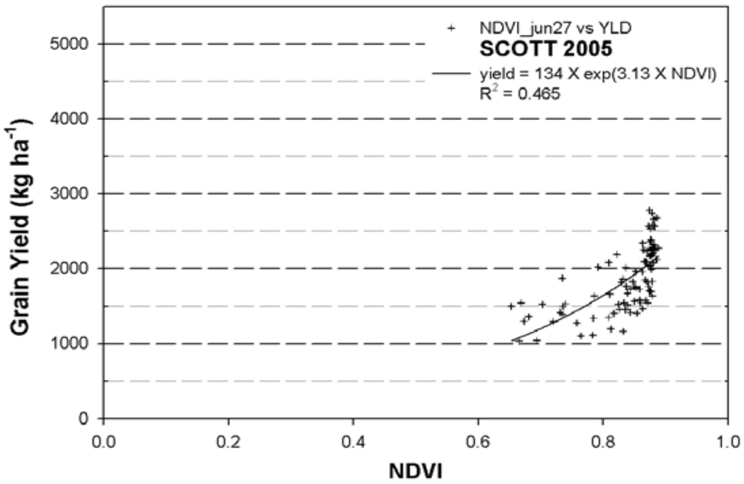

Figure D-51. Canola yield versus NDVI on June 27, 2005 at Scott, SK when the crop was at growth stage 3.1 (Harper and Berkenkamp 1975).

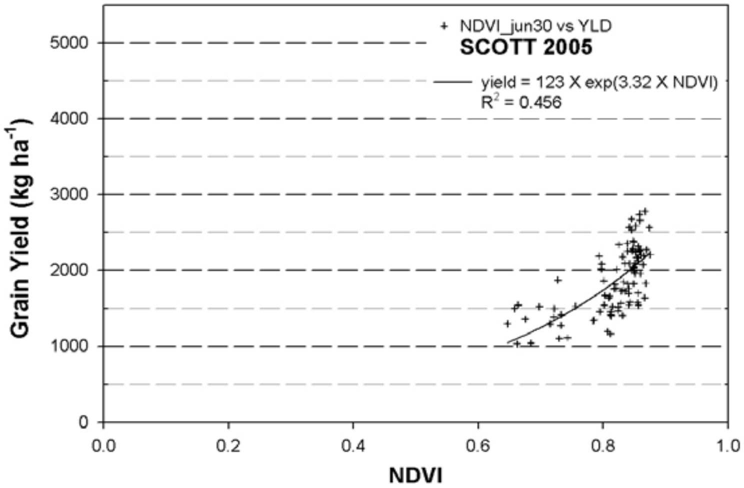

Figure D-52. Canola yield versus NDVI on June 30, 2005 at Scott, SK when the crop was at growth stage 3.3 (Harper and Berkenkamp 1975).

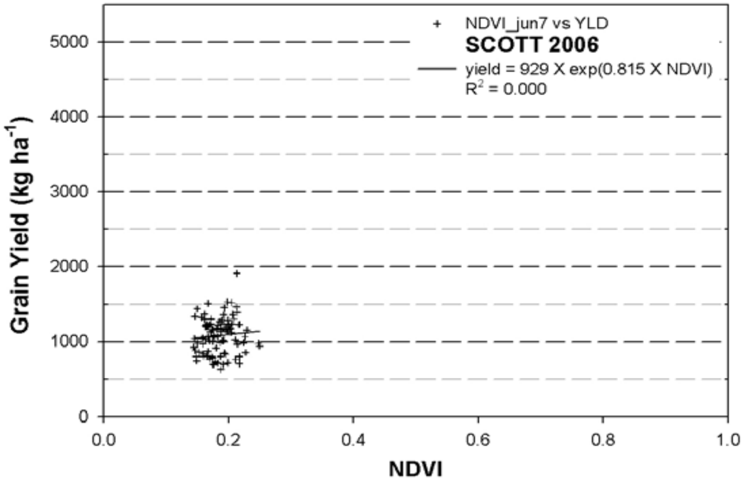

Figure D-53. Canola yield versus NDVI on June 7, 2006 at Scott, SK when the crop was at growth stage 2.2 (Harper and Berkenkamp 1975).

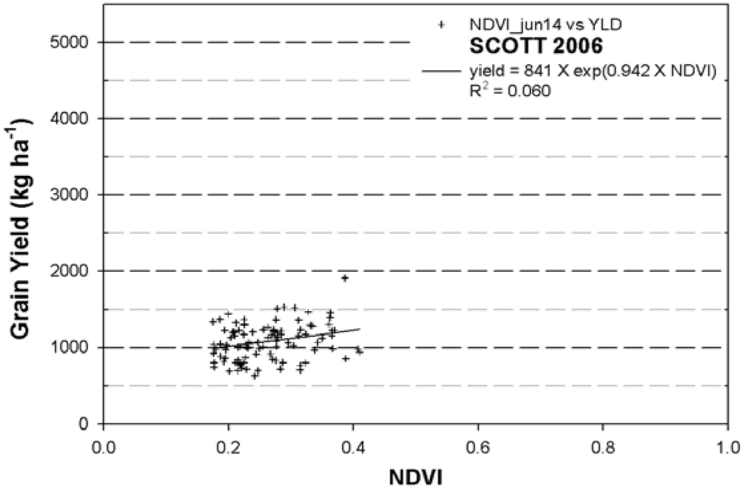

Figure D-54. Canola yield versus NDVI on June 14, 2006 at Scott, SK when the crop was at growth stage 2.4 (Harper and Berkenkamp 1975).

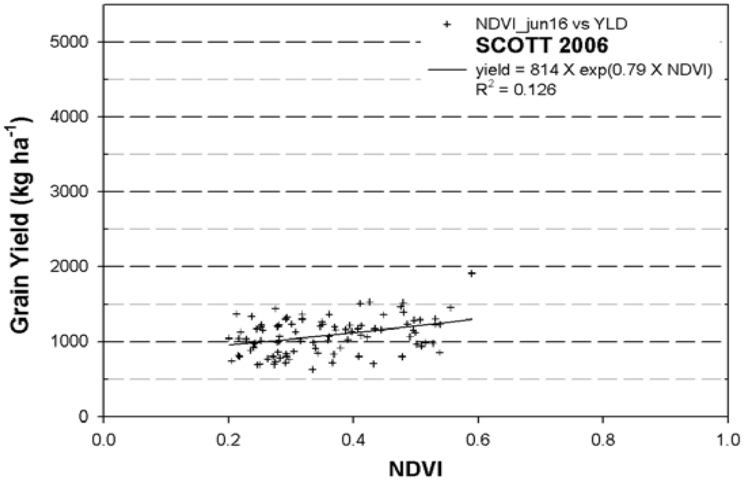

Figure D-55. Canola yield versus NDVI on June 16, 2006 at Scott, SK when the crop was at growth stage 2.4 – 2.5 (Harper and Berkenkamp 1975).

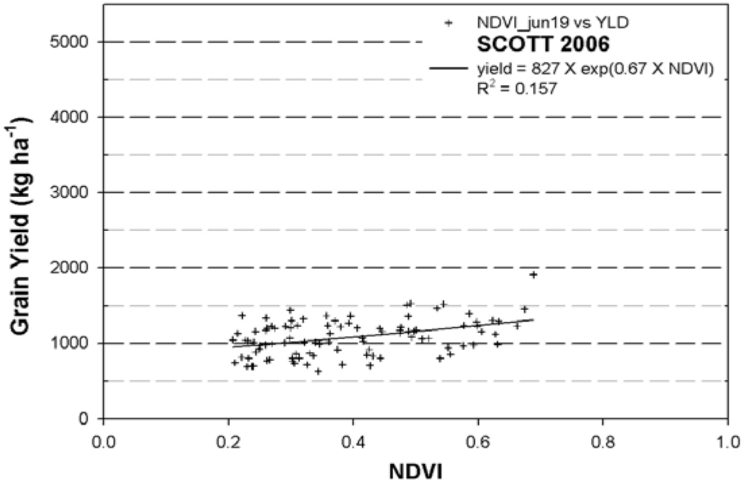

Figure D-56. Canola yield versus NDVI on June 19, 2006 at Scott, SK when the crop was at growth stage 2.5 (Harper and Berkenkamp 1975).

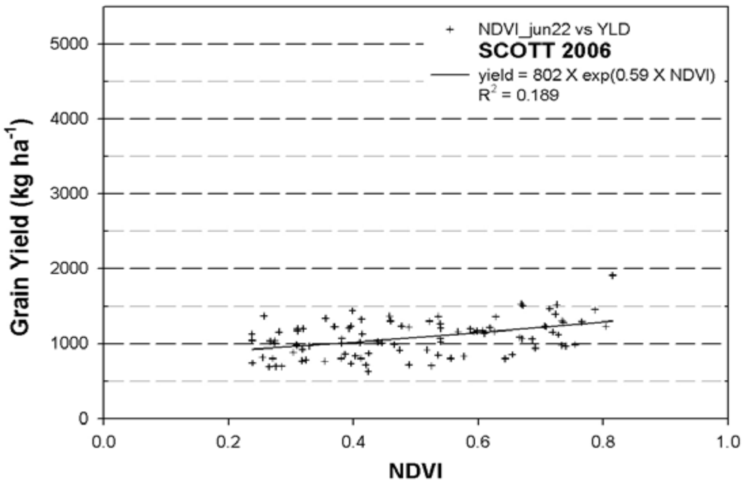

Figure D-57. Canola yield versus NDVI on June 22, 2006 at Scott, SK when the crop was at growth stage 2.5 (Harper and Berkenkamp 1975).

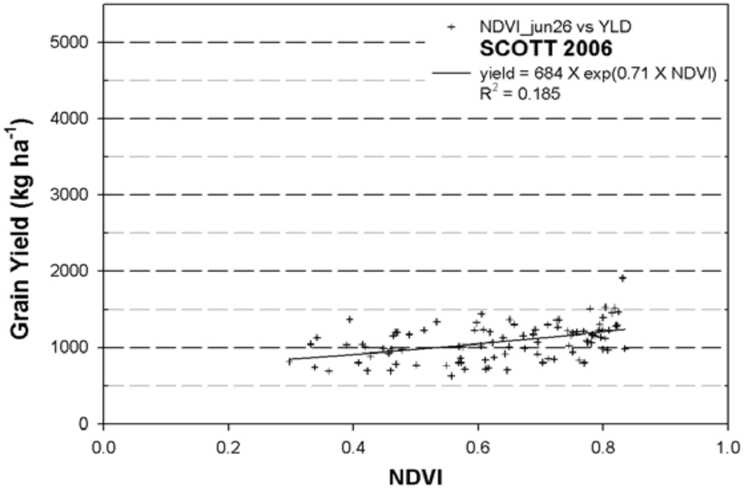

Figure D-58. Canola yield versus NDVI on June 26, 2006 at Scott, SK when the crop was at growth stage 2.6 – 3.2 (Harper and Berkenkamp 1975).

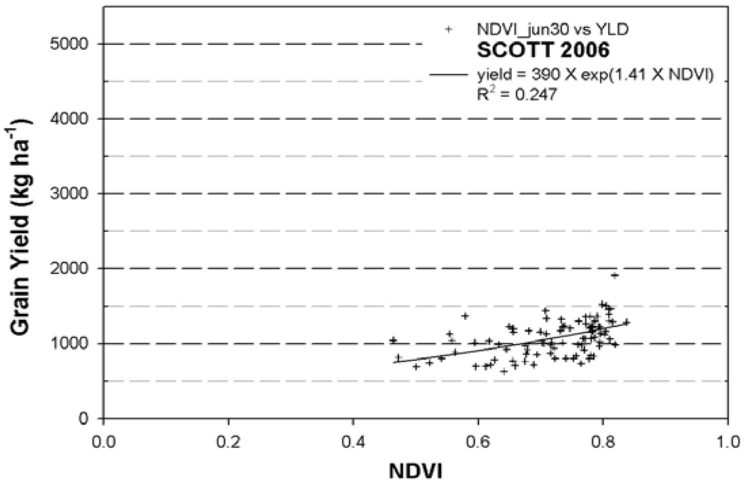

Figure D-59. Canola yield versus NDVI on June 30, 2006 at Scott, SK when the crop was at growth stage 3.3 – 4.1 (Harper and Berkenkamp 1975).

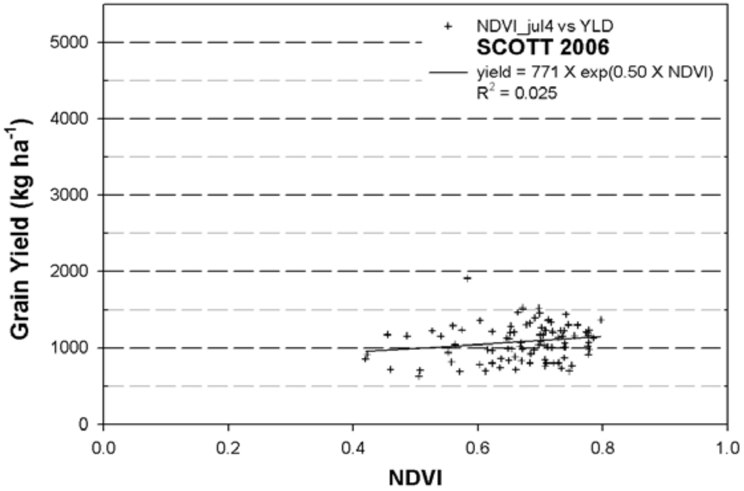

Figure D-60. Canola yield versus NDVI on July 4, 2006 at Scott, SK when the crop was at growth stage 4.3 (Harper and Berkenkamp 1975).

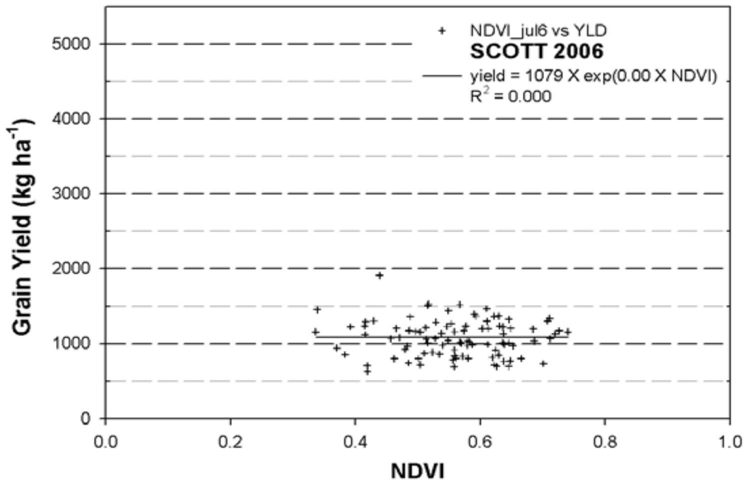

Figure D-61. Canola yield versus NDVI on July 6, 2006 at Scott, SK when the crop was at growth stage 4.3 – 4.4 (Harper and Berkenkamp 1975).

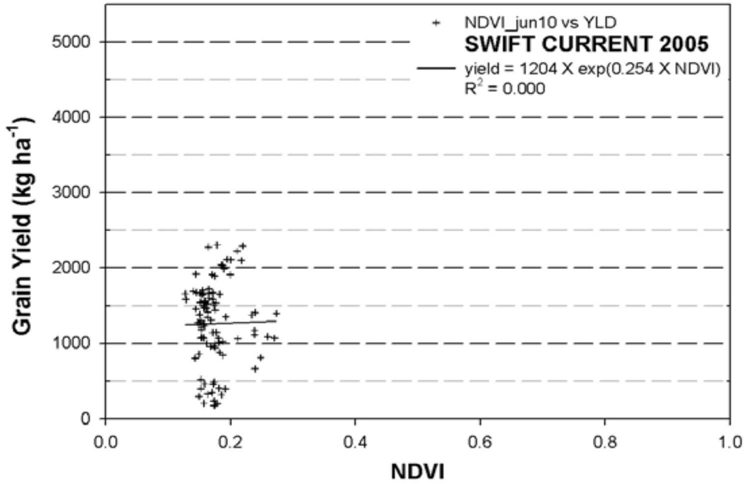

Figure D-62. Figure 60. Canola yield versus NDVI on June 10, 2005 at Swift Current, SK when the crop was at growth stage 2.1 (Harper and Berkenkamp 1975).

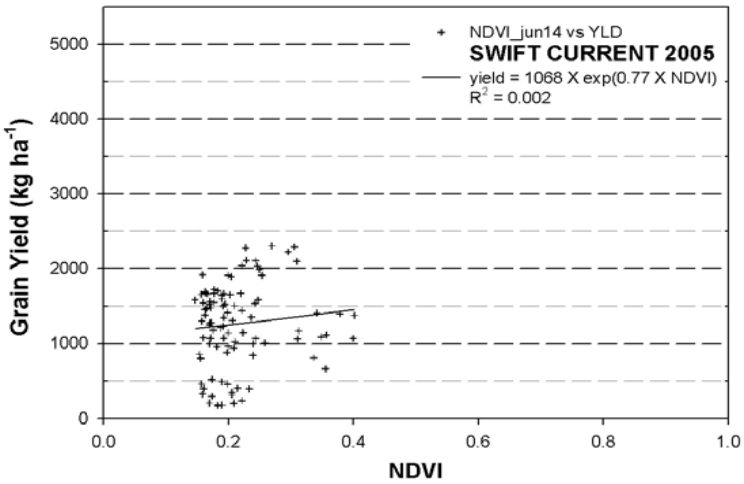

Figure D-63. Canola yield versus NDVI on June 14, 2005 at Swift Current, SK when the crop was at growth stage 2.2 (Harper and Berkenkamp 1975).

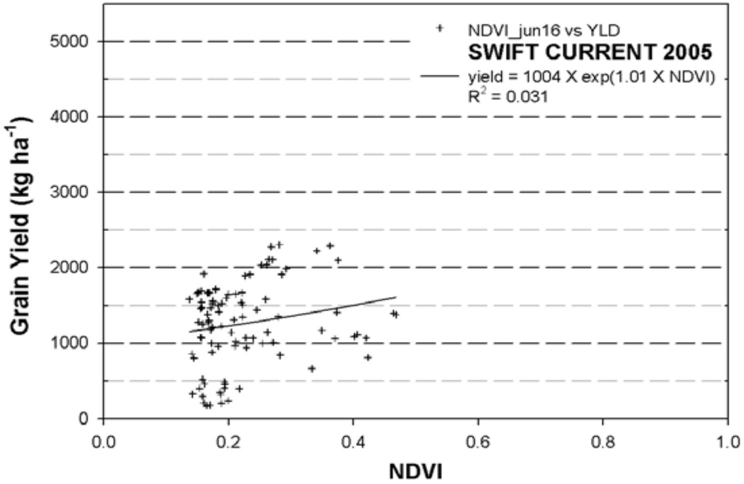

Figure D-64. Canola yield versus NDVI on June 16, 2005 at Swift Current, SK when the crop was at growth stages 2.2 – 2.3 (Harper and Berkenkamp 1975).

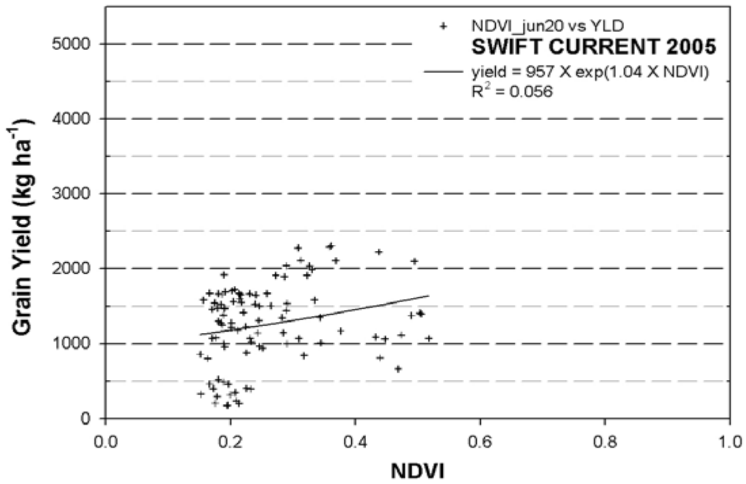

Figure D-65. Canola yield versus NDVI on June 20, 2005 at Swift Current, SK when the crop was at growth stage 2.4 – 2.5 (Harper and Berkenkamp 1975).

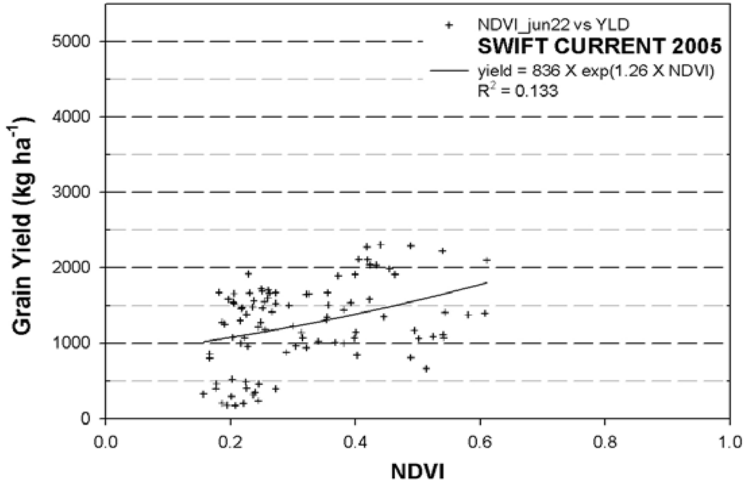

Figure D-66. Canola yield versus NDVI on June 22, 2005 at Swift Current, SK when the crop was at growth stage 2.5 – 3.1 (Harper and Berkenkamp 1975).

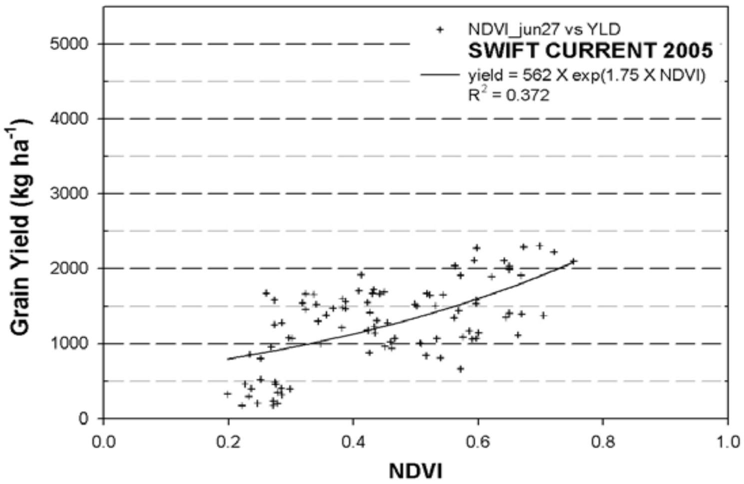

Figure D-67 Canola yield versus NDVI on June 27, 2005 at Swift Current, SK when the crop was at growth stages 3.2 – 4.1 (Harper and Berkenkamp 1975).

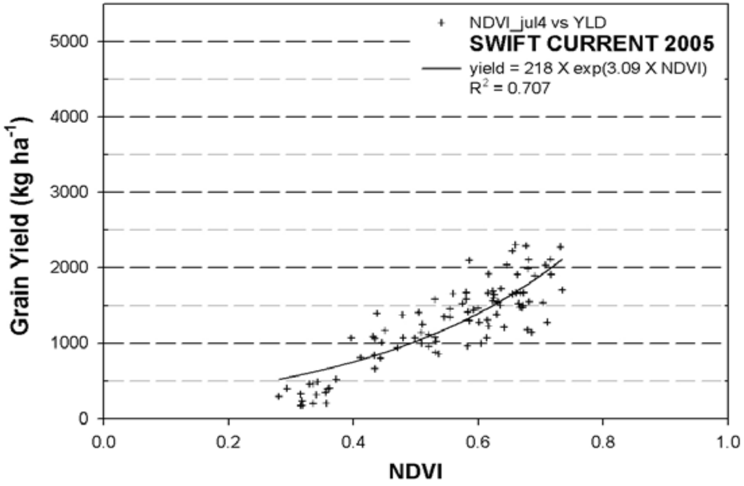

Figure D-68. Canola yield versus NDVI on July 4, 2005 at Swift Current, SK when the crop was at growth stage 4.1 – 4.2 (Harper and Berkenkamp 1975).

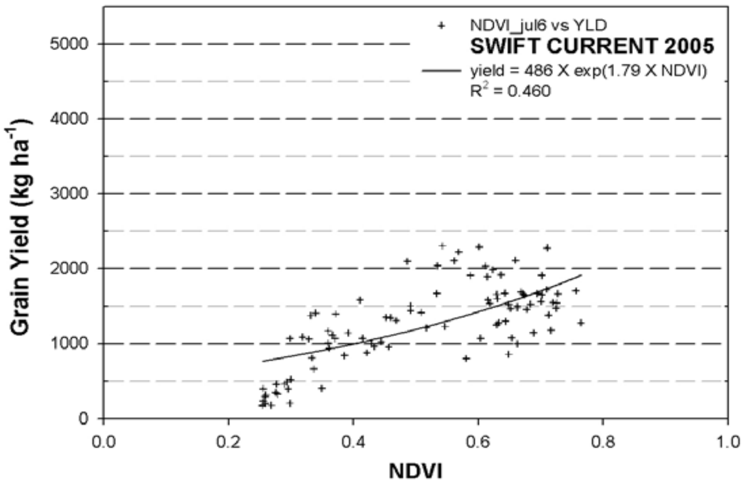

Figure D-69. Canola yield versus NDVI on July 6, 2005 at Swift Current, SK when the crop was at growth stages 4.2 – 4.3 (Harper and Berkenkamp 1975).

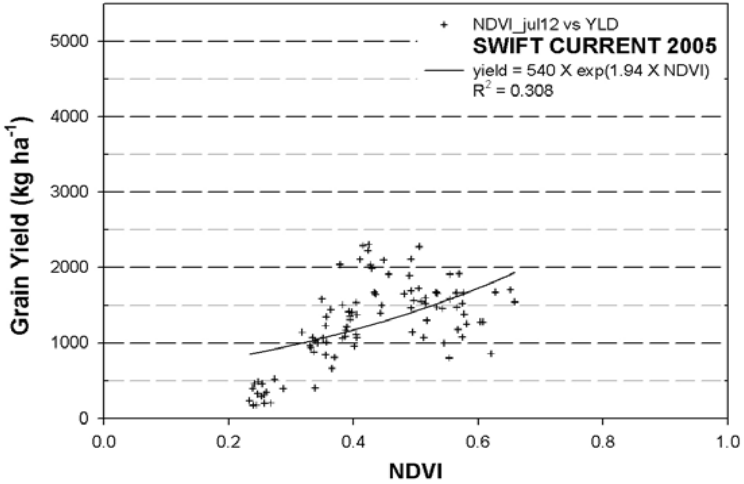

Figure D-70. Canola yield versus NDVI on July 12, 2005 at Swift Current, SK when the crop was at growth stages 4.3 – 4.4 (Harper and Berkenkamp 1975).

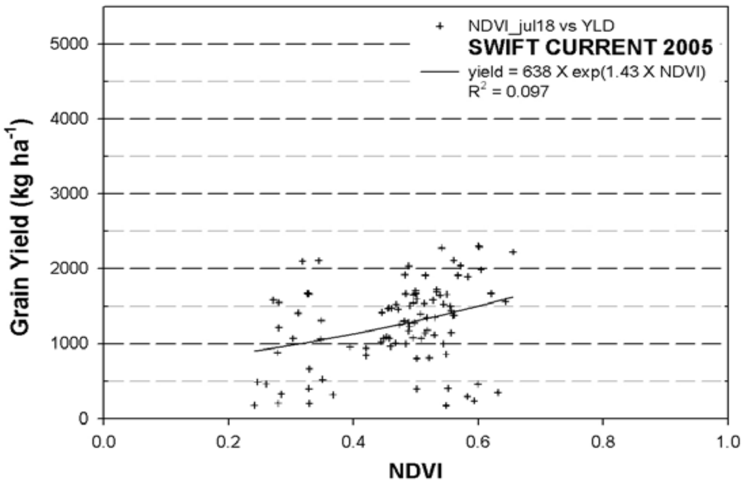

Figure D-71. Canola yield versus NDVI on July 18, 2005 at Swift Current, SK when the crop was at growth stages 5.1 – 5.2 (Harper and Berkenkamp 1975).

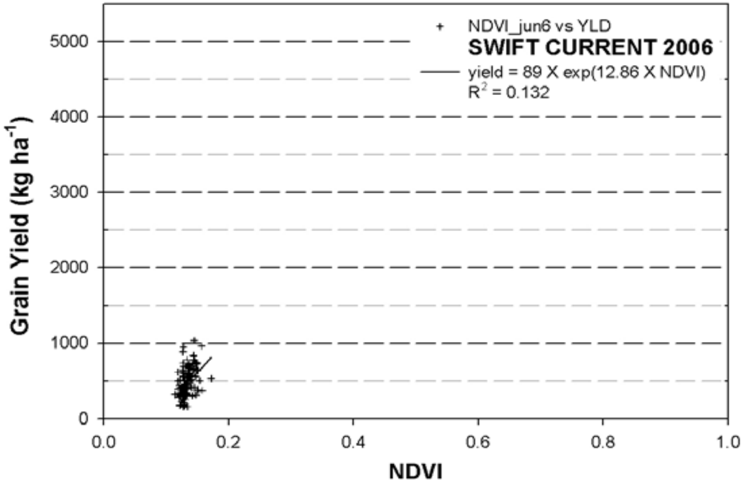

Figure D-72. Canola yield versus NDVI on June 6, 2006 at Swift Current, SK when the crop was at growth stages 1 – 2.1 (Harper and Berkenkamp 1975).

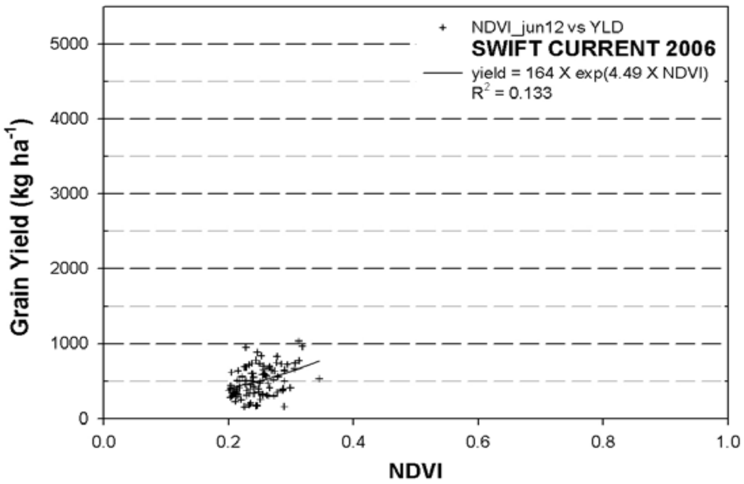

Figure D-73. Canola yield versus NDVI on June 12, 2006 at Swift Current, SK when the crop was at growth stage 2.1 – 2.2 (Harper and Berkenkamp 1975).

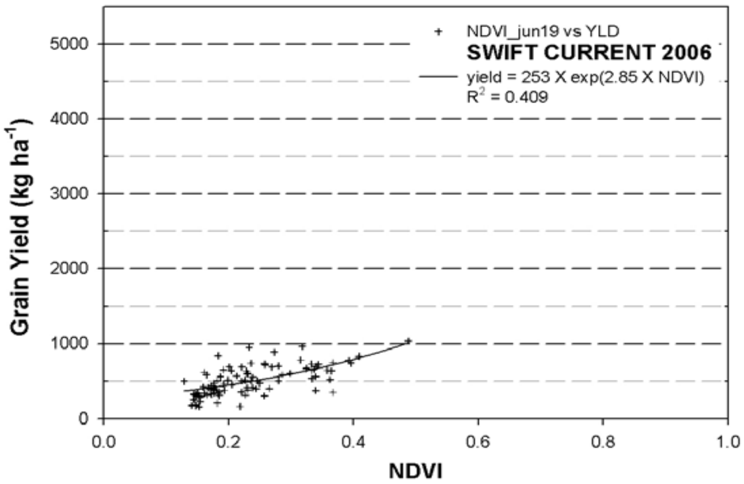

Figure D-75. Canola yield versus NDVI on June 19, 2006 at Swift Current, SK when the crop was at growth stages 2.3 – 2.5 (Harper and Berkenkamp 1975).

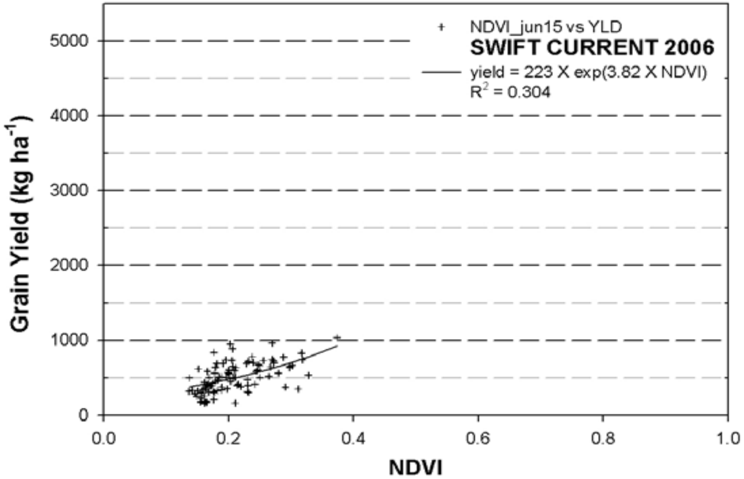

Figure D-74. Canola yield versus NDVI on June 15, 2006 at Swift Current, SK when the crop was at growth stage 2.3 – 24 (Harper and Berkenkamp 1975).

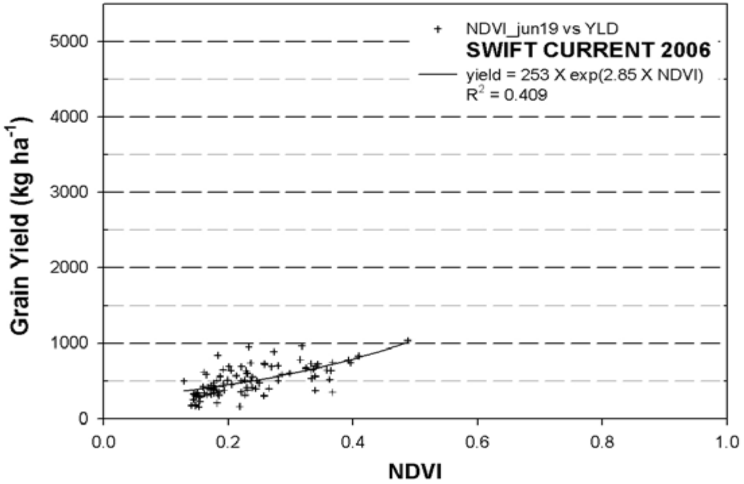

Figure D-76. Canola yield versus NDVI on June 21, 2006 at Swift Current, SK when the crop was at growth stages 2.4 – 2.5 (Harper and Berkenkamp 1975).

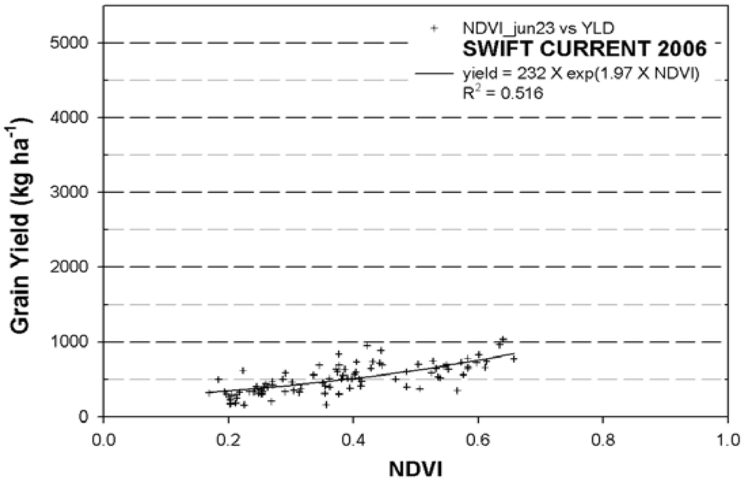

Figure D-77. Canola yield versus NDVI on June 23, 2006 at Swift Current, SK when the crop was at growth stages 2.5 – 2.6 (Harper and Berkenkamp 1975).

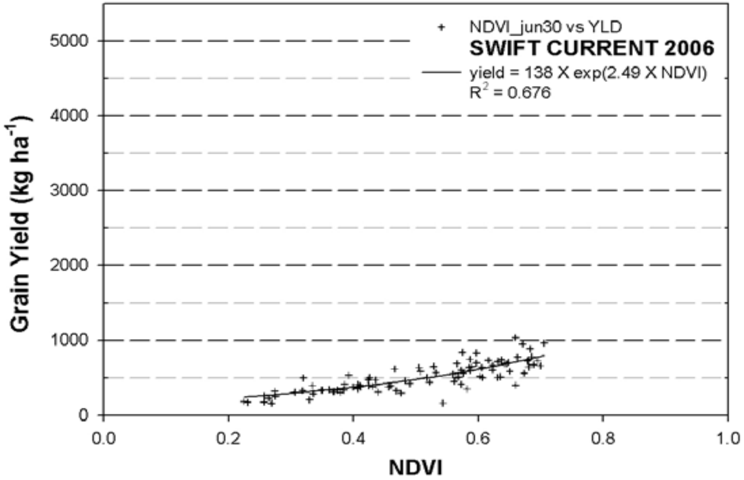

Figure D-78. Canola yield versus NDVI on June 30, 2006 at Swift Current, SK when the crop was at growth stages 3.3 – 4.1 (Harper and Berkenkamp 1975).

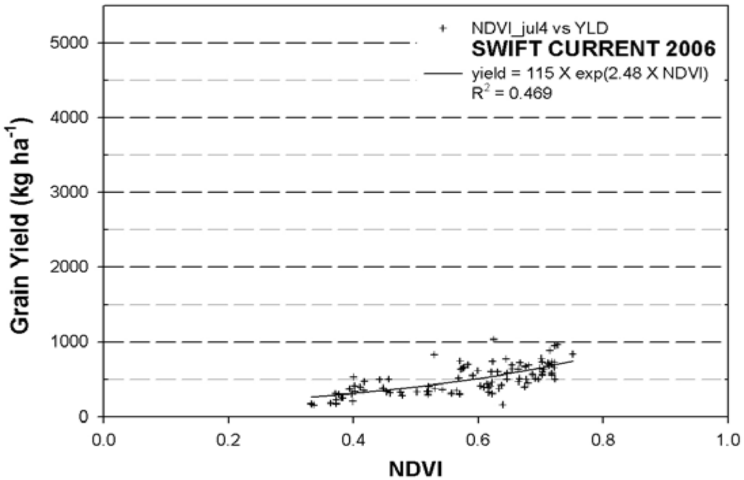

Figure D-79. Canola yield versus NDVI on July 4, 2006 at Swift Current, SK when the crop was at growth stages 4.2 – 4.4 (Harper and Berkenkamp 1975).

APPENDIX E – GRAPHICAL REPRESENTATION OF COMBINED, STANDARDIZED YIELD DATA PRESENTED IN TABLES 3.10 AND 3.11

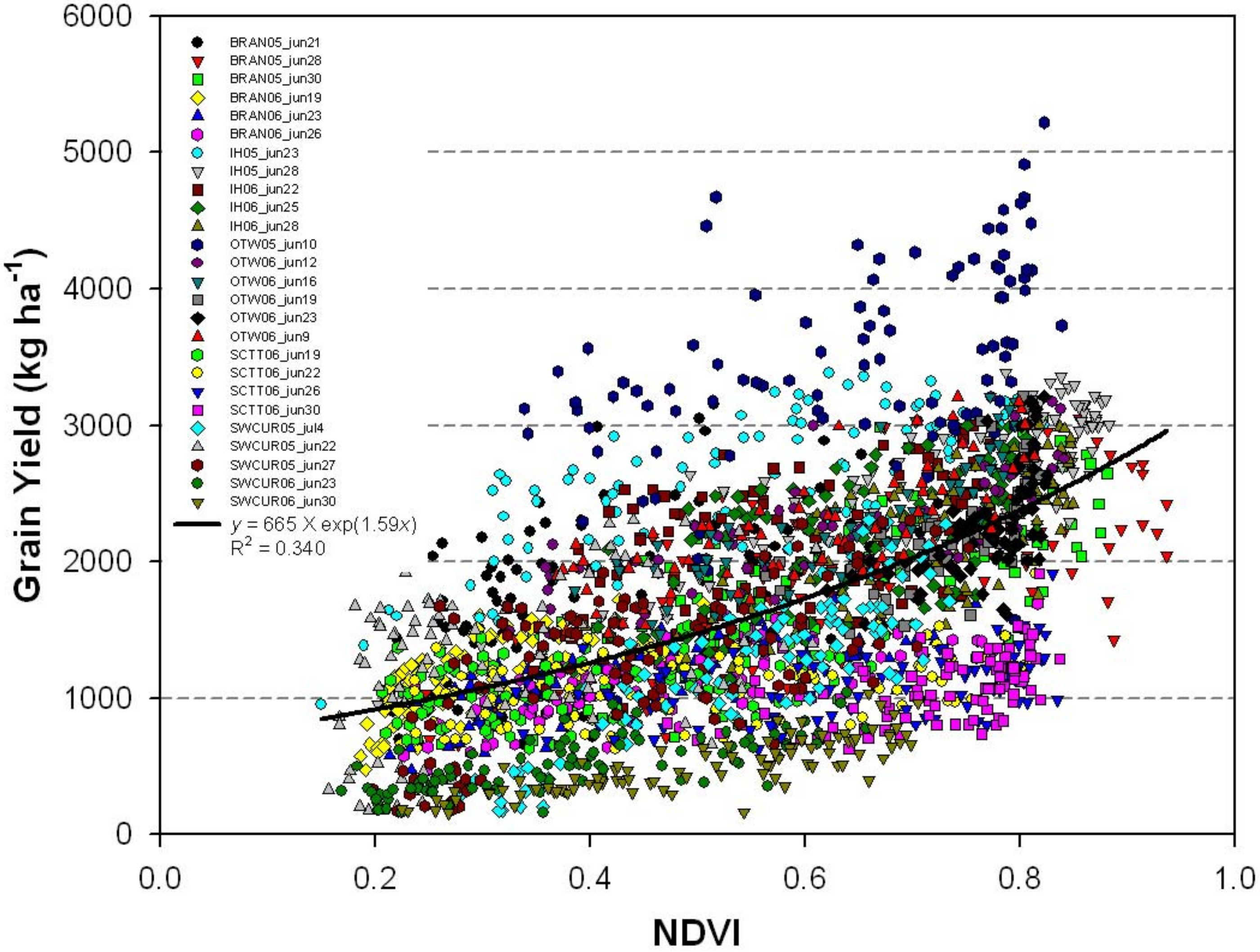

Figure E-1 Canola seed yield versus normalized difference vegetation index (R^2=0.340) for all site-years presented in Chapter 3 except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

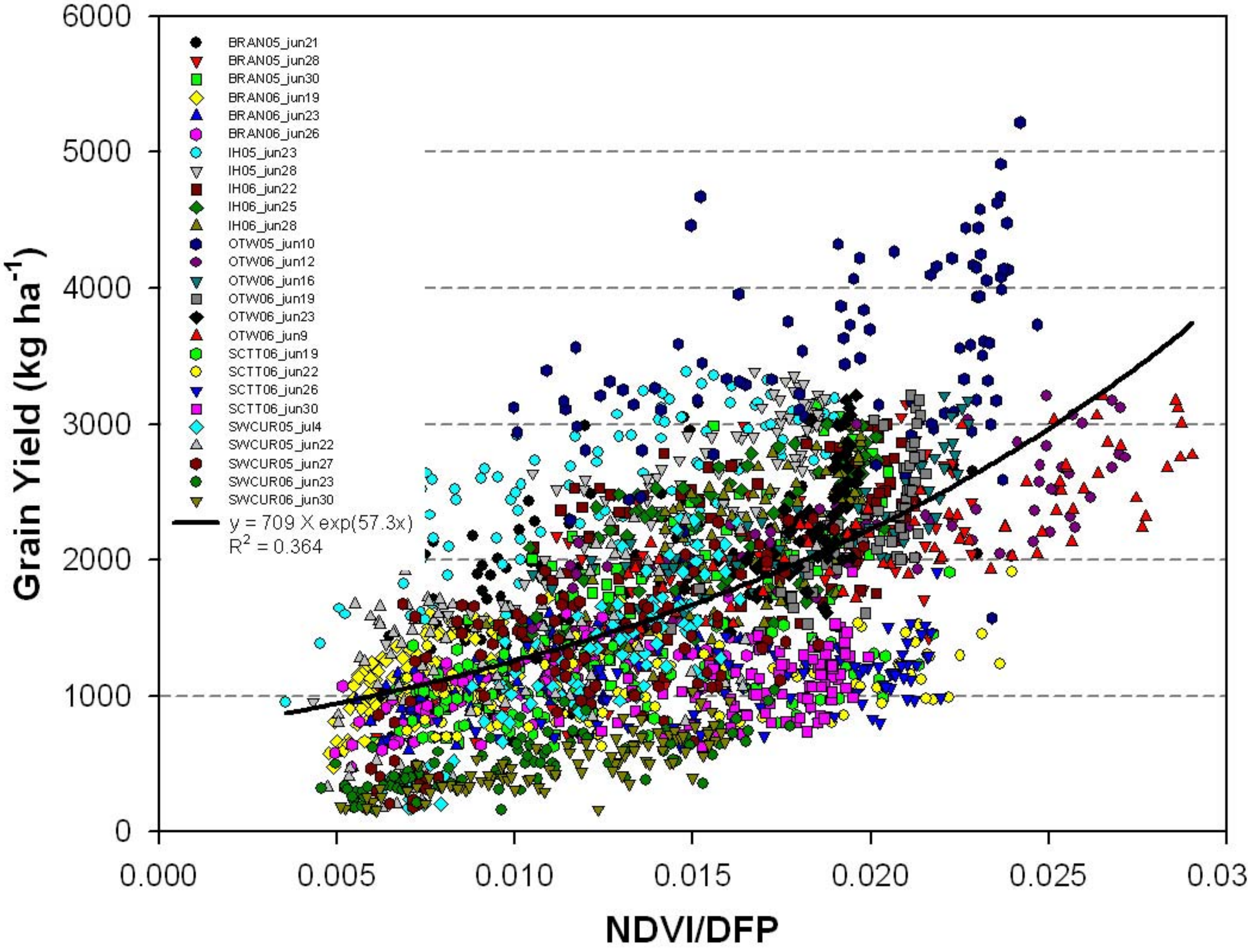

Figure E-2. Canola seed yield versus normalized difference vegetation index divided by days from planting (R^2=0.364) for all site-years in Chapter 3 except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

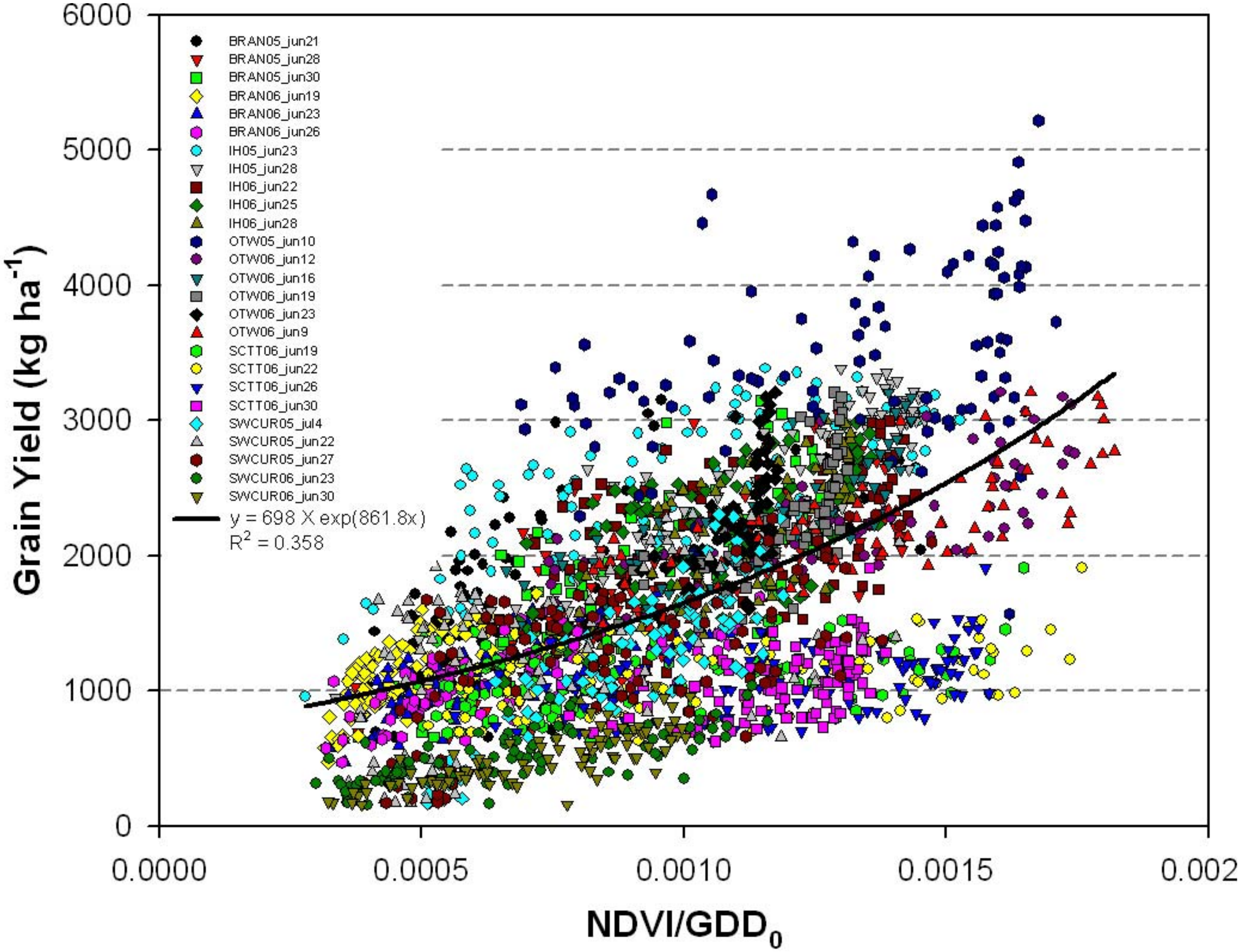

Figure E-3. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base 0°C; R^2=0.358) for all site-years in Chapter 3 except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

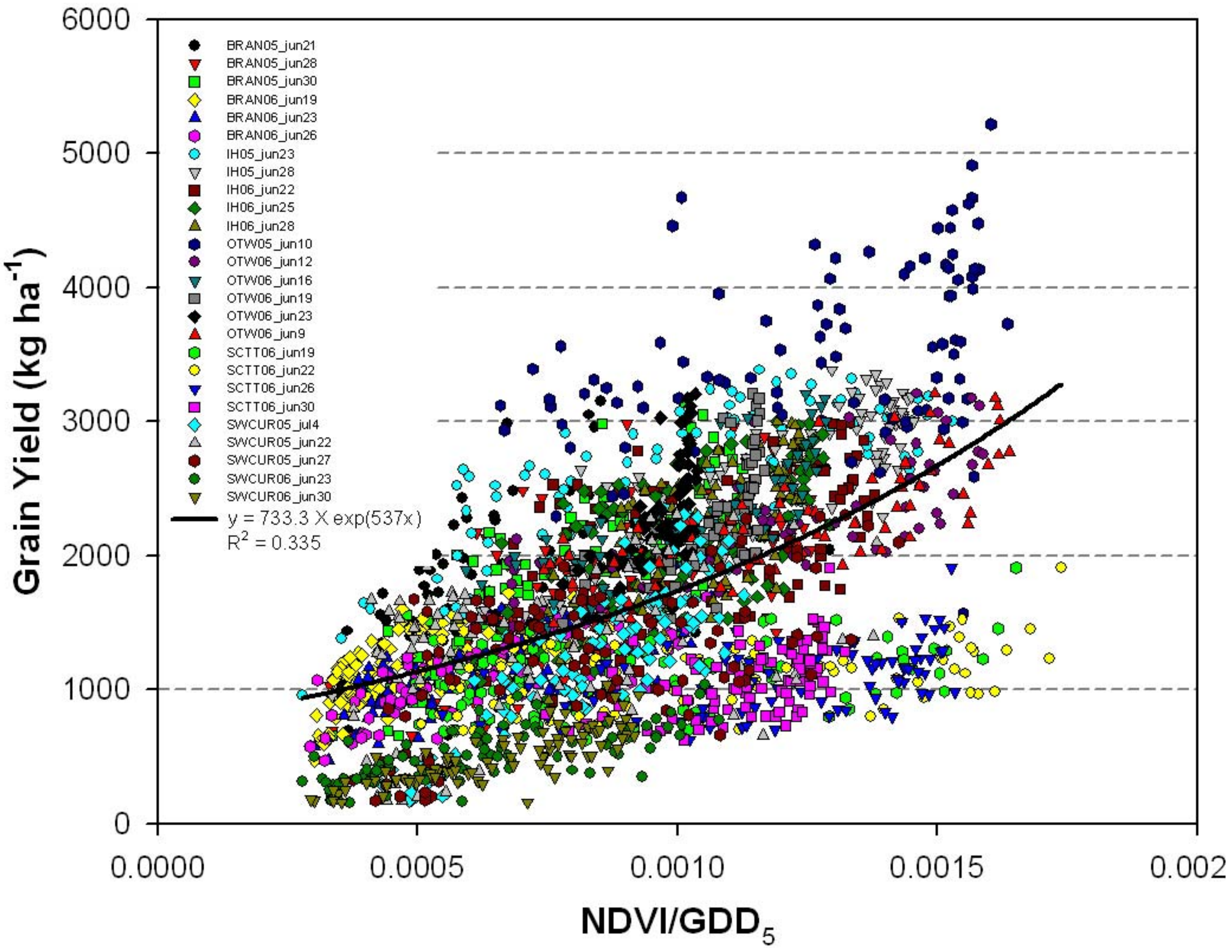

Figure E-4. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base 5°C; R^2=0.335) for all site-years in Chapter 3 except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

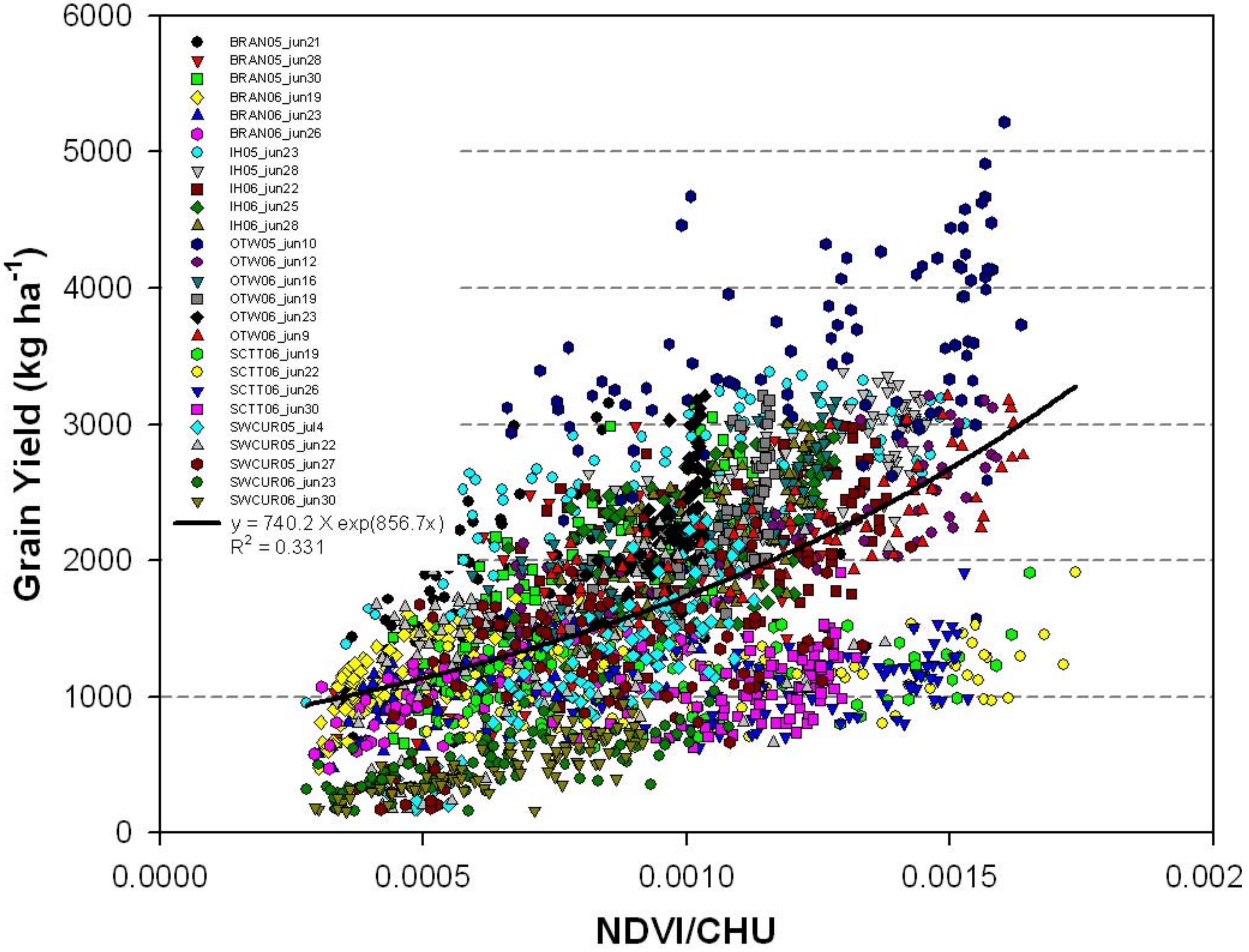

Figure E-5. Canola seed yield versus normalized difference vegetation index divided by corn heat units (R^2=0.331) for all site-years in Chapter 3 except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

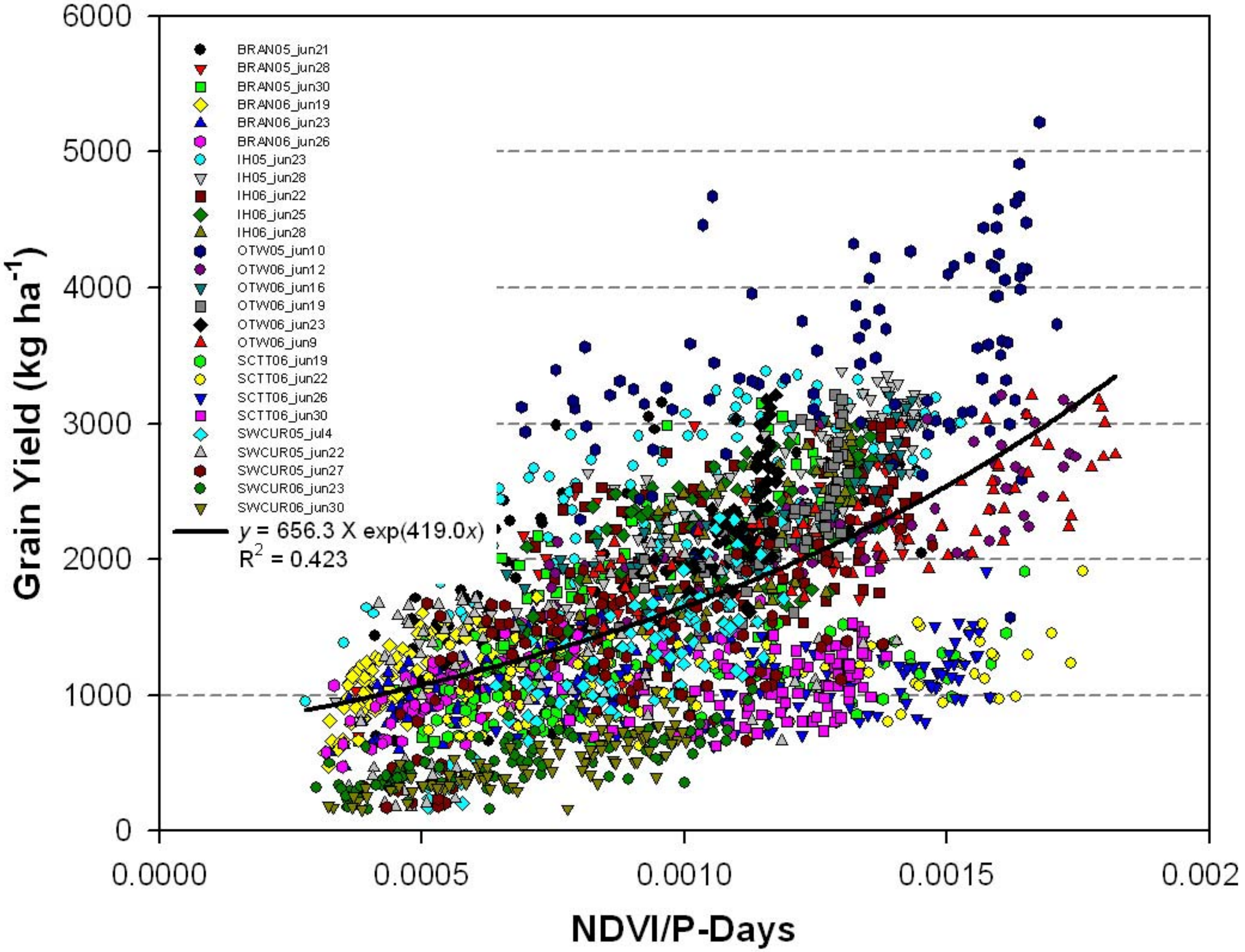

Figure E-6. Canola seed yield versus normalized difference vegetation index divided by physiological days (R^2=0.423) for all site-years in Chapter 3 except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

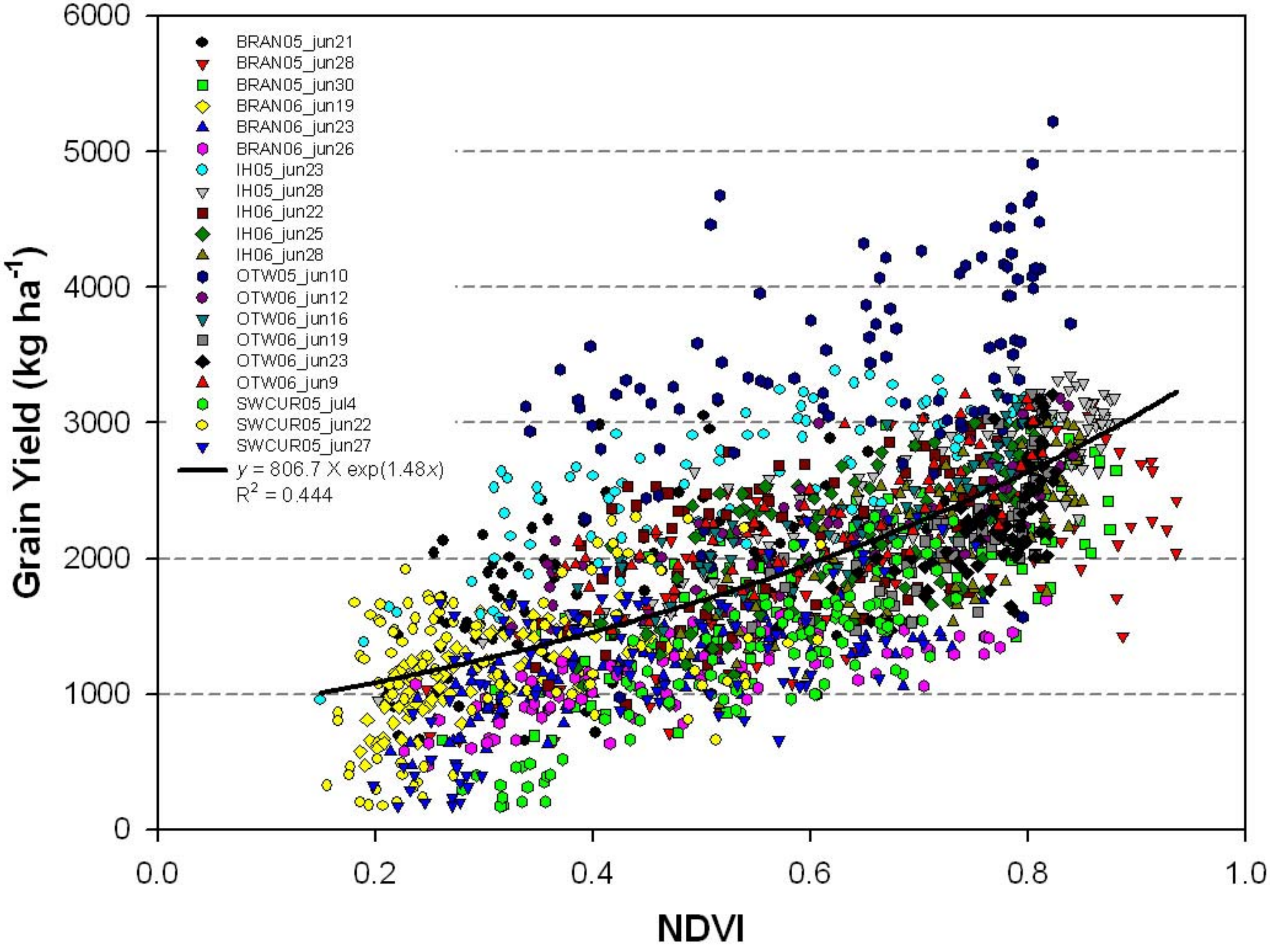

Figure E-7. Canola seed yield versus normalized difference vegetation index (R^2=0.444) for all site-years in Chapter 3 except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

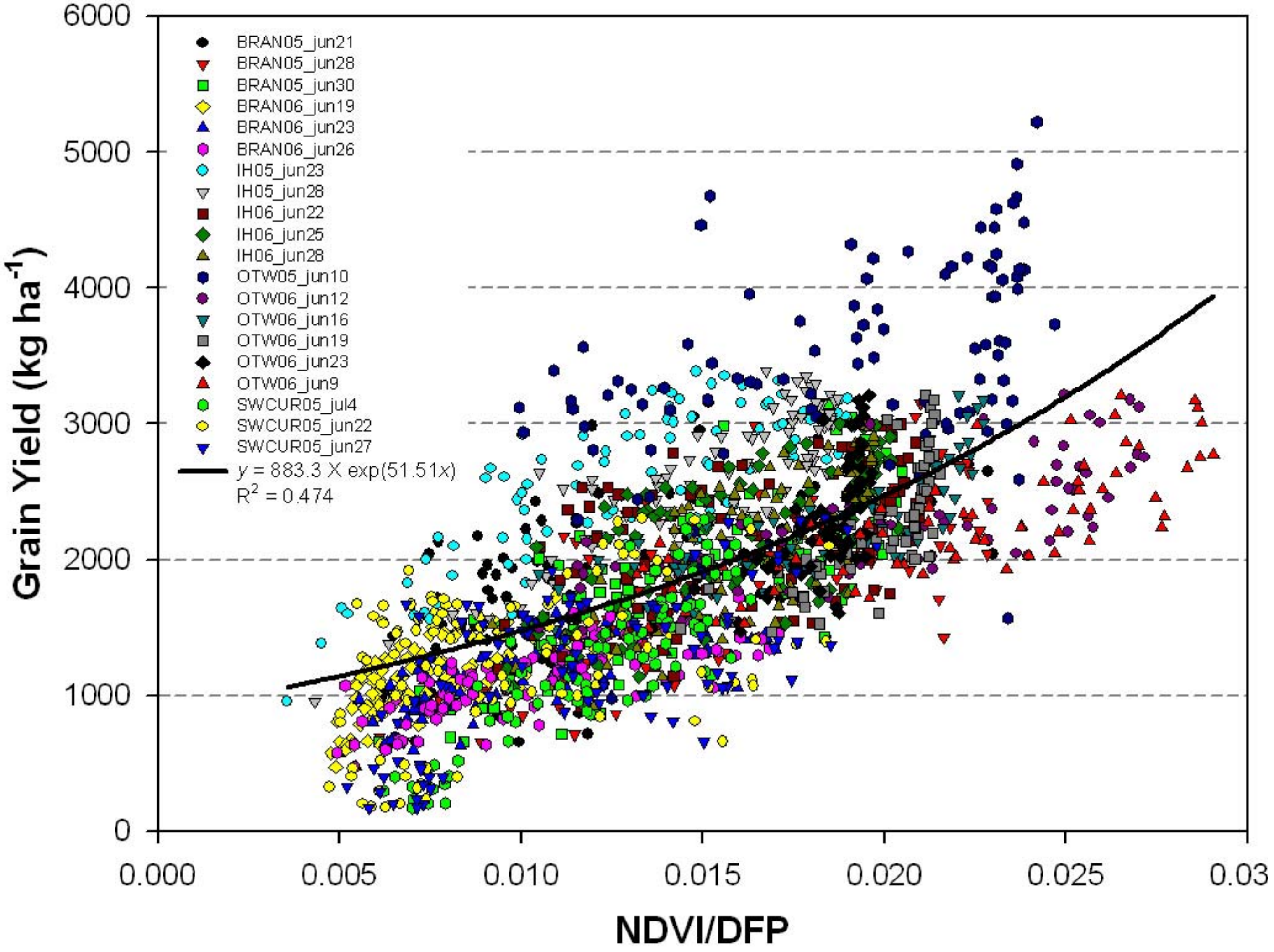

Figure E-8. Canola seed yield versus normalized difference vegetation index divided by days from planting (R^2=0.474)) for all site-years in Chapter 3 except for for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

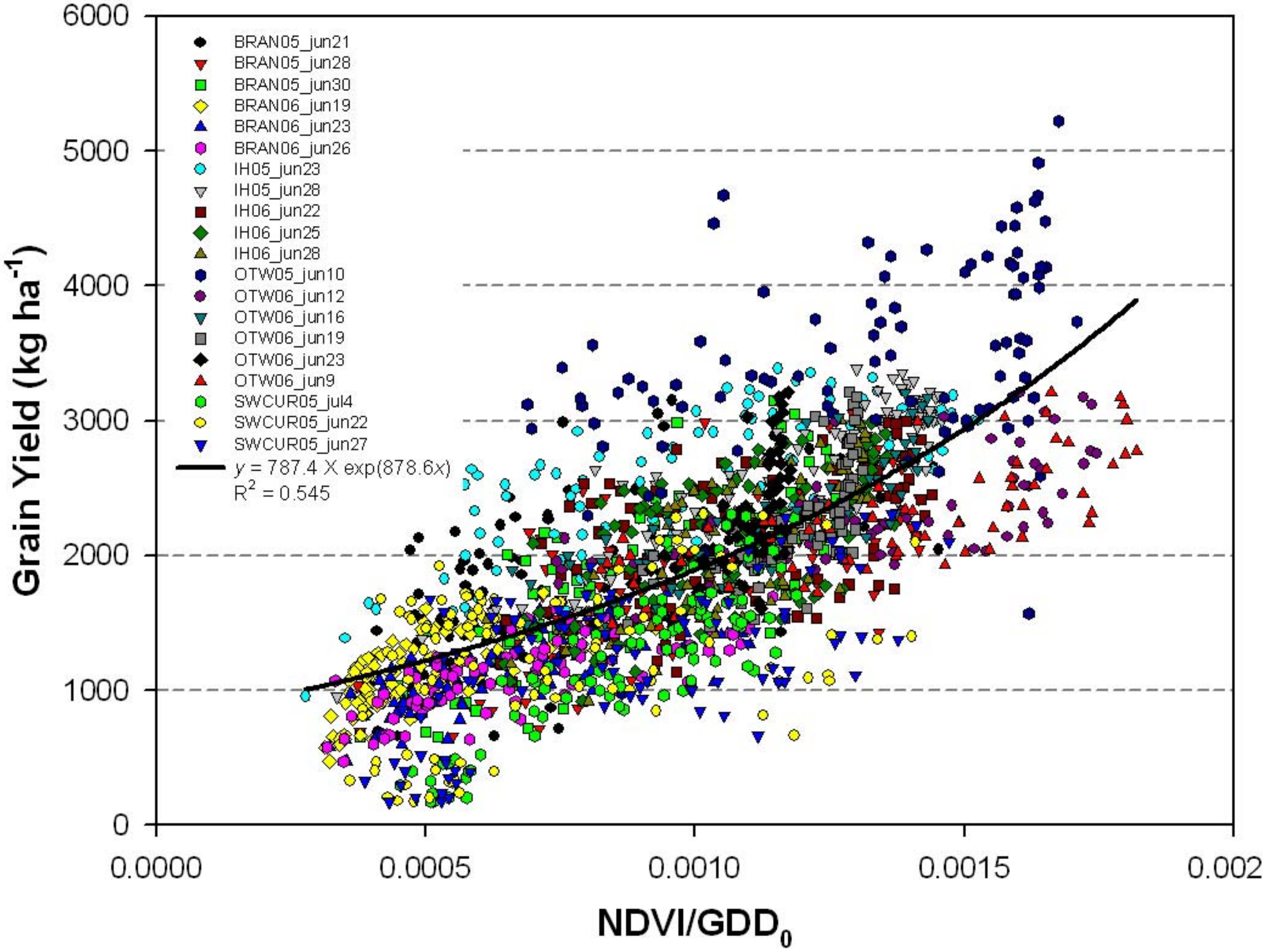

Figure E-9. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base 0°C; R^2=0545) for all site-years in Chapter 3 except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

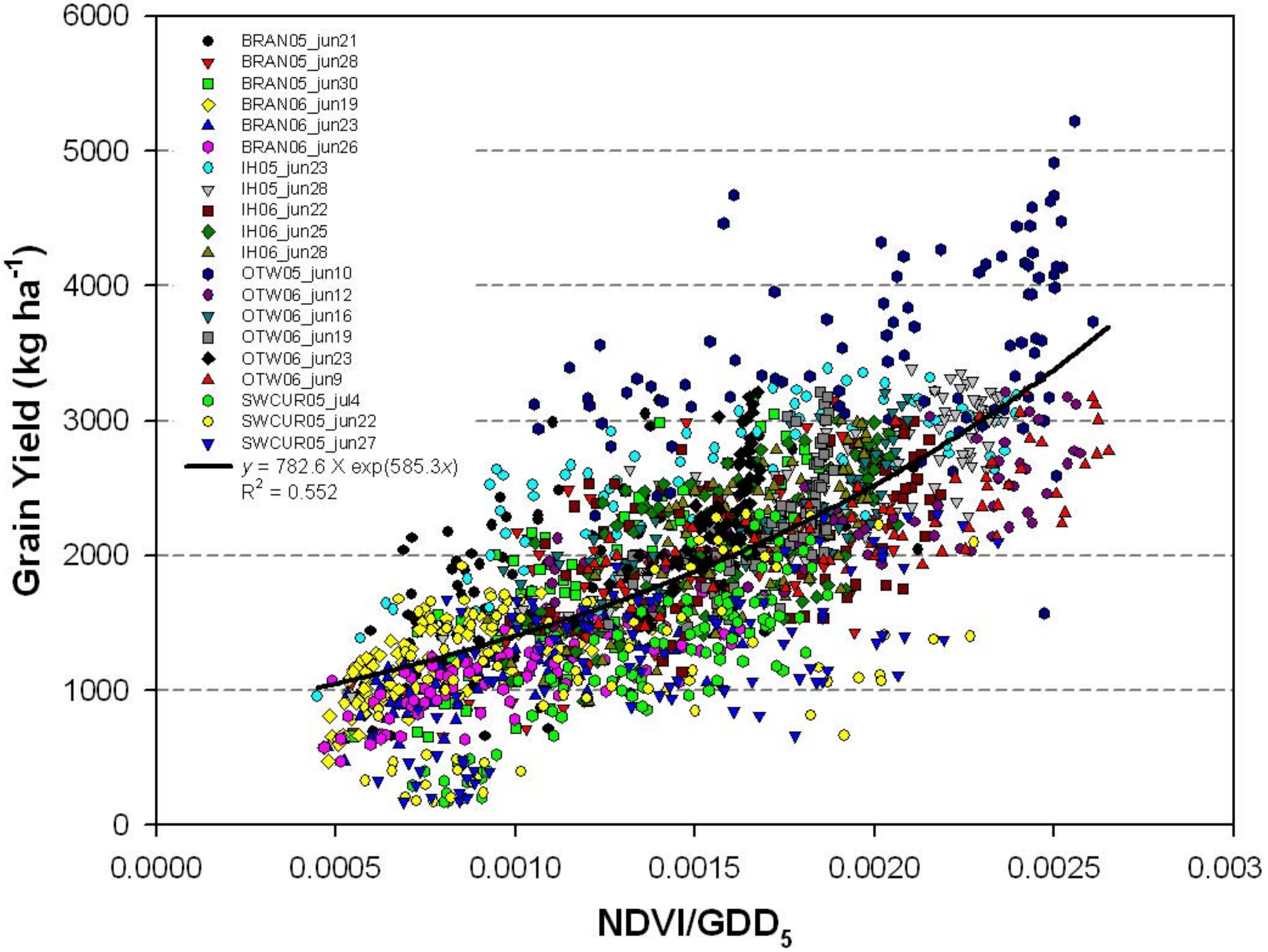

Figure E-10. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base 5°C; R^2=0.552) for all site-years in Chapter 3 except for for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

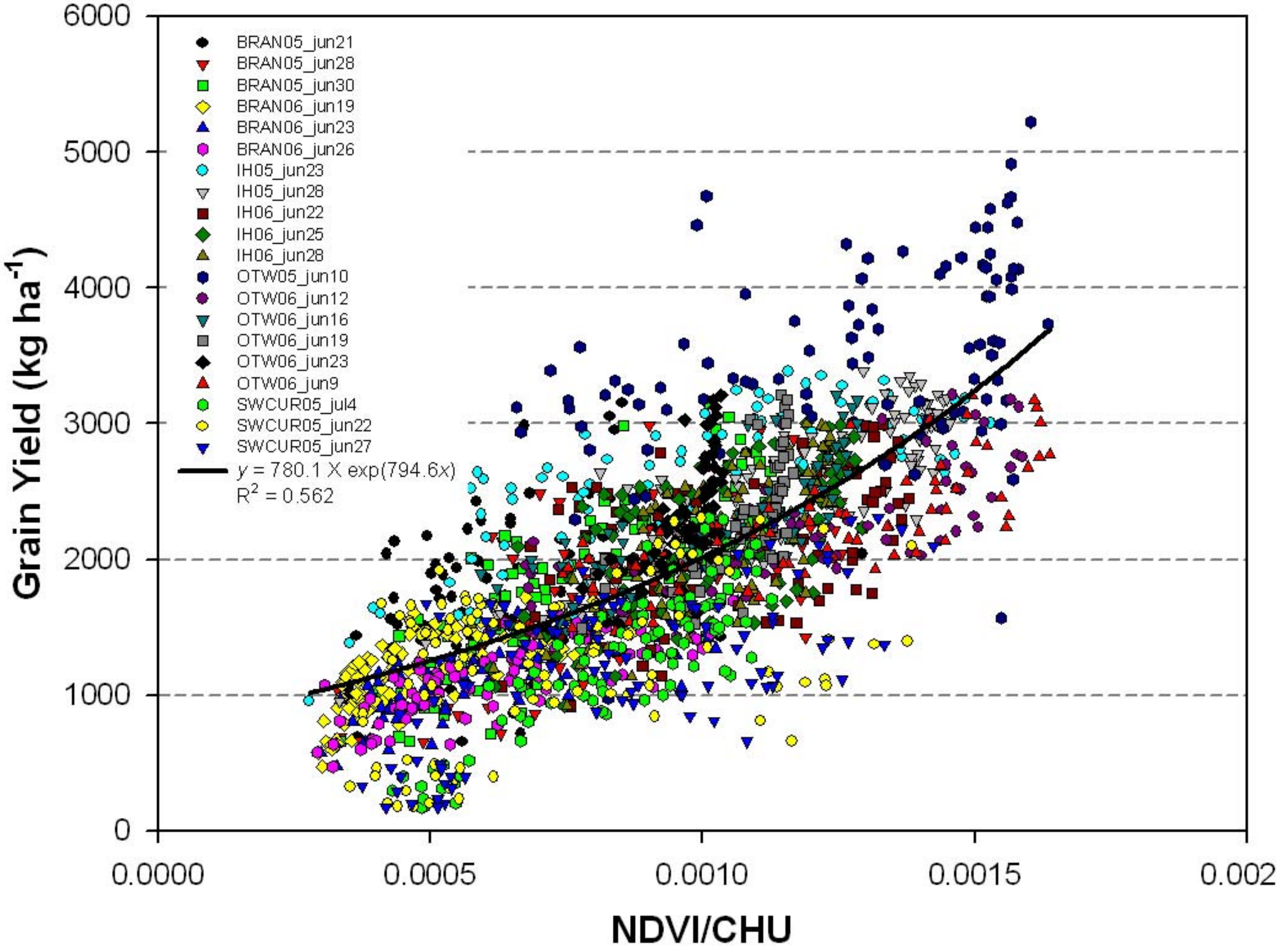

Figure E-11. Canola seed yield versus normalized difference vegetation index divided by corn heat units (R^2=0.562) for all site-years in Chapter 3 except for for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

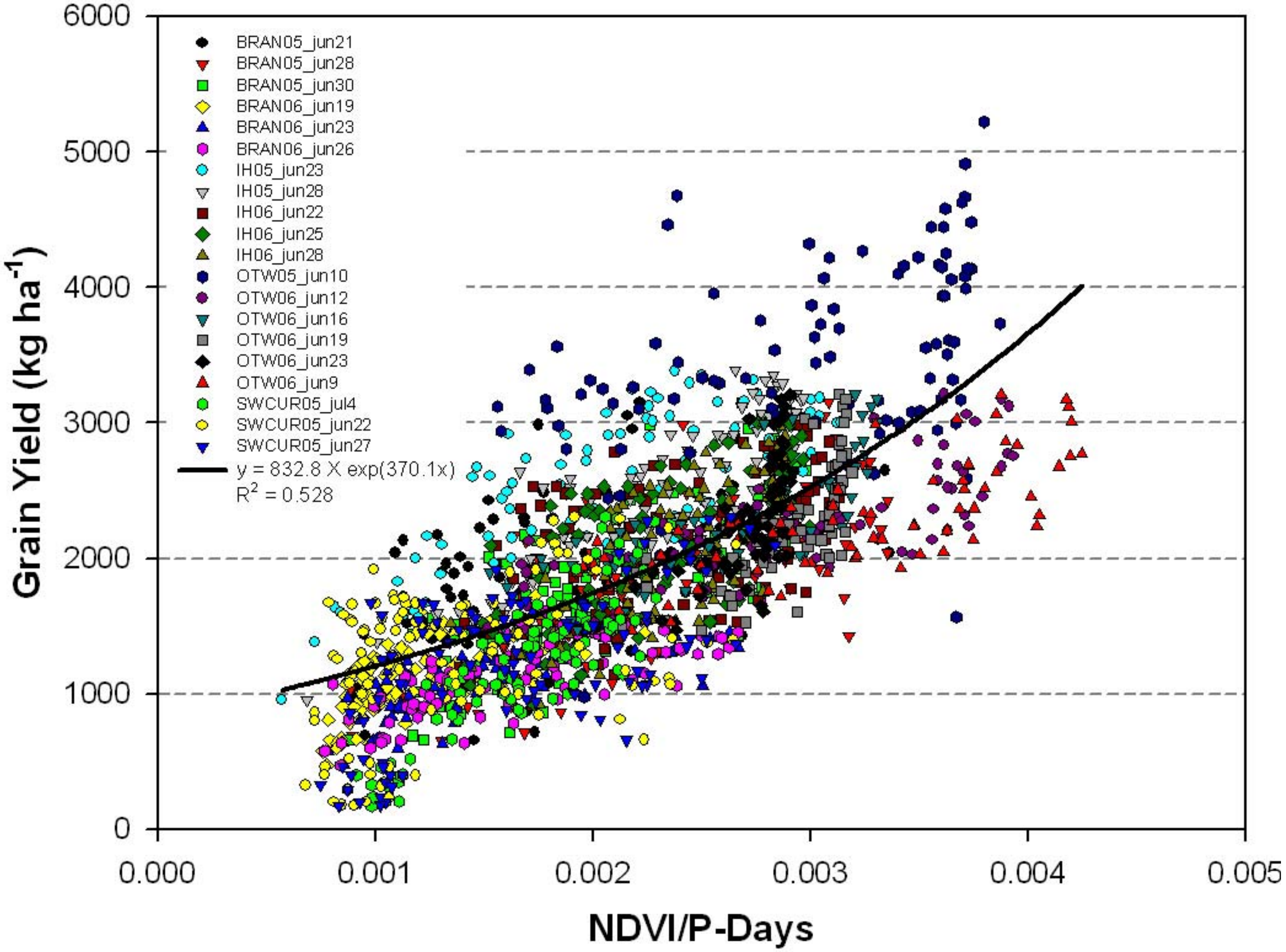

Figure E-12. Canola seed yield versus normalized difference vegetation index divided by physiological days (R^2=0.528) for all site-years in Chapter 3 except for for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

APPENDIX F – SCATTER PLOTS OF EMPIRICAL DATA USED TO DERIVE THE YIELD POTENTIAL CURVES USED IN CHAPTERS FOUR AND FIVE IN THE 2005 AND 2006 GROWING SEASONS

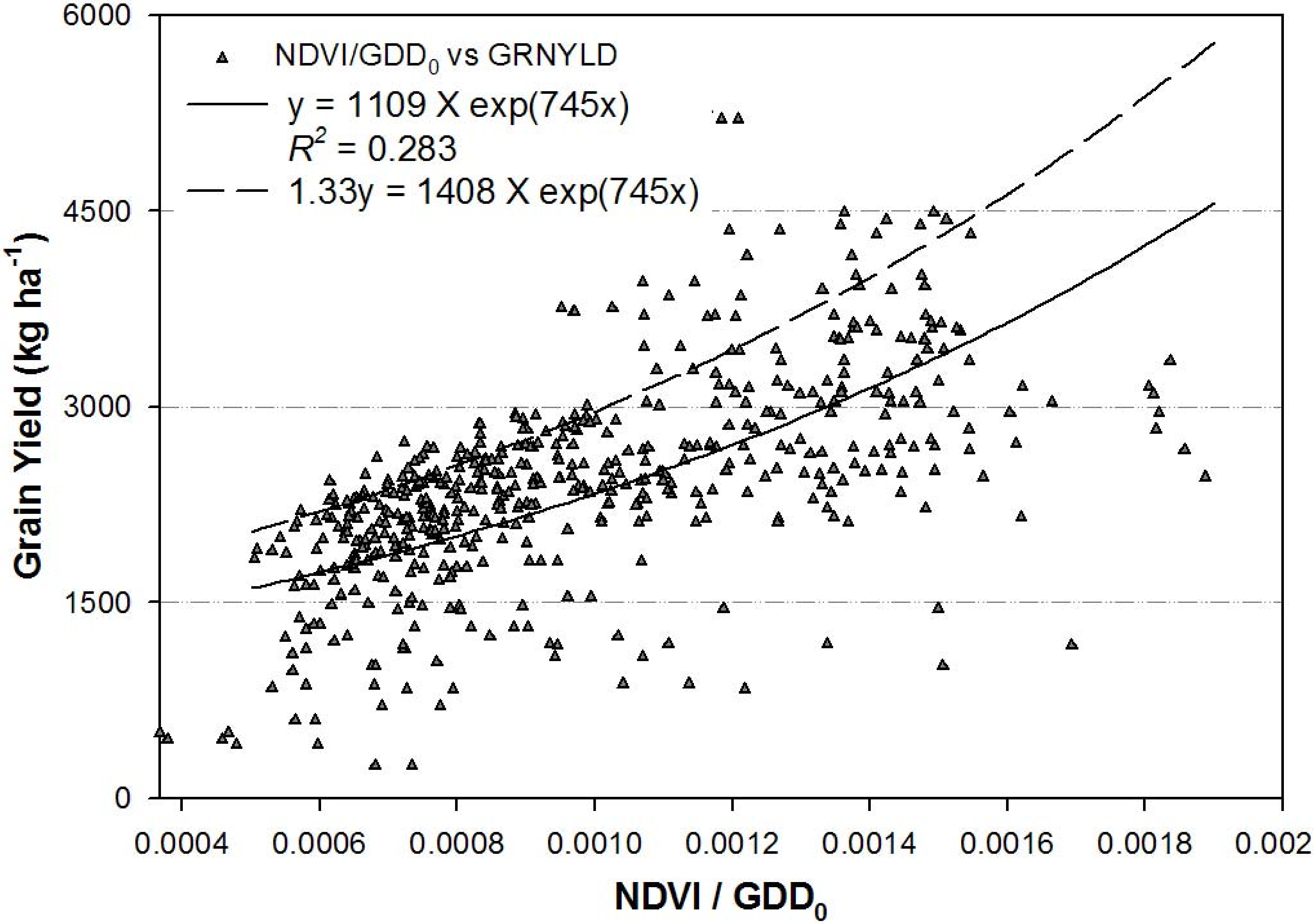

Figure F-1. Empirical data used to derive yield potential curves used in Chapters 4 and 5 during the 2005 growing season.

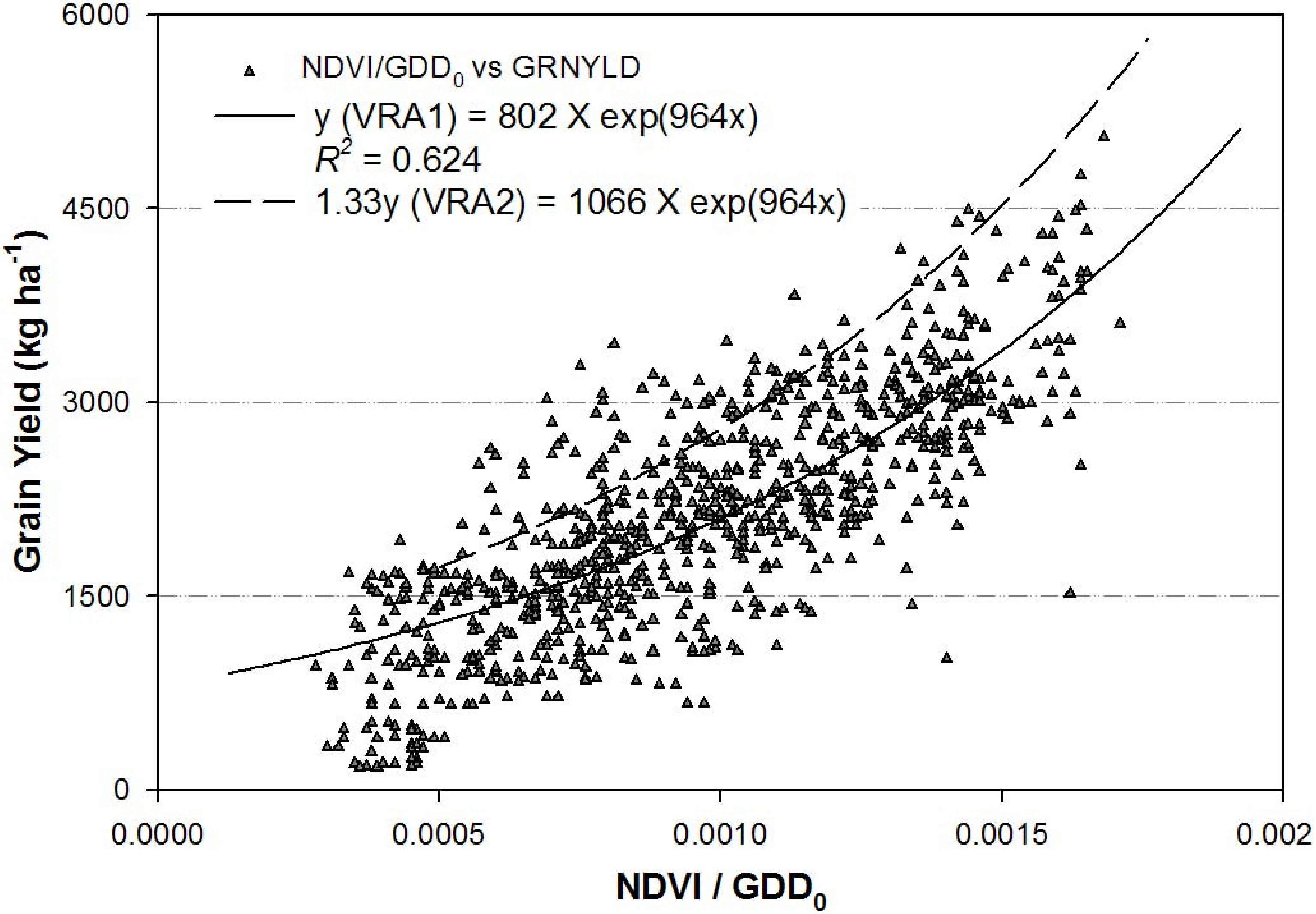

Figure F-2. Empirical data used to derive yield potential curves used in Chapters 4 and 5 during the 2005 growing season.

APPENDIX G – ADDITIONAL SUMMARY TABLES FOR FALL RESIDUAL SOIL NO_3-N LEVELS REPORTED IN CHAPTER FOUR

Table G.1. Post-harvest soil residual NO_3-N (kg N ha^{-1}) for the zero to 15 cm soil profile for canola plots managed under various N management strategies at Indian Head and Scott in the 2005 and 2006 growing seasons.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management		fall residual soil NO_3-N kg ha^{-1} 0 -15cm		
Check	10.3	n/a	11.2	7.0abc
N Rich (NR)	18.1	n/a	21.0	9.0ab
Farmer Practice (FP)	13.0	n/a	11.8	6.2bc
Reduced N (RN)	11.0	n/a	na	na
Split / Fixed (SF)	12.4	n/a	22.4	9.8a
Variable Rate 1 (VRA1)	na	n/a	na	6.7bc
Variable Rate 2 (VRA2)	15.4	n/a	13.1	5.0c
LSD[z] (α = 0.05)	**ns**	n/a	**ns**	**2.81**
		Analysis of Variance		
Source		p > F		
Treatment	0.119	n/a	0.252	**0.021***
Replicate	0.793	n/a	0.309	[v]
Residual C.V. (%)	29.8	n/a	54.2	26.0
		Selected Contrasts		
		p-value		
Check vs Rest	0.112	n/a	0.247	0.750
NR vs RN+SF+VRA[x]	**0.041**	n/a	0.561	0.122
FP vs RN+SF+VRA[x]	0.963	n/a	0.288	0.360
VRA vs NR[w]	0.359	n/a	0.259	**0.016***
VRA vs FP[w]	0.417	n/a	0.838	0.812
VRA vs SF[w]	0.817	n/a	0.189	**0.003***

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc).

[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

[x] RN treatment excluded from contrast at Scott

[w] Contrasts include both VRA treatments in 2006 at both sites

[v] Data from Scott 2006 analyzed as a completely randomized design

na – Treatment not included at this site-year.

ns – F-test not significant at $p \leq 0.05$

* Significant at $p \leq 0.05$

Table G.2. Post-harvest soil residual NO_3-N (kg N ha^{-1}) for the 15 – 60 cm soil profile for canola plots managed under various N management strategies at Indian Head and Scott in the 2005 and 2006 growing seasons.

	Indian Head		Scott	
	2005	**2006**	**2005**	**2006**
Nitrogen Management	fall residual soil NO_3-N kg ha^{-1} 15 - 60cm			
Check	10.4c	n/a	11.5	4.5
N Rich (NR)	41.6a	n/a	21.0	6.4
Farmer Practice (FP)	15.6bc	n/a	12.0	4.2
Reduced N (RN)	13.7bc	n/a	na	na
Split / Fixed (SF)	21.2b	n/a	18.0	5.3
Variable Rate 1 (VRA1)	na	n/a	na	4.5
Variable Rate 2 (VRA2)	13.4bc	n/a	12.2	5.0
LSD[z] ($\alpha = 0.05$)	**8.84**	n/a	**ns**	**ns**
	Analysis of Variance			
Source	p > F			
Treatment	**<0.001***	n/a	0.192	0.367
Replicate	0.279	n/a	0.250	[v]
Residual C.V. (%)	30.4	n/a	42.1	30.5
	Selected Contrasts			
	p-value			
Check vs Rest	**0.005***	n/a	0.245	0.470
NR vs RN+SF+VRA[x]	**<0.001***	n/a	0.163	0.107
FP vs RN+SF+VRA[x]	0.898	n/a	0.454	0.407
VRA vs NR[w]	**<0.001***	n/a	0.098	0.088
VRA vs FP[w]	0.593	n/a	0.967	0.587
VRA vs SF[w]	0.079	n/a	0.263	0.556

[z] Data analyzed using the PROC GLM procedure of SAS 9.1 (SAS Institute Inc).

[y] SF treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FP treatment

[x] RN treatment excluded from contrast at Scott

[w] Contrasts include both VRA treatments in 2006 at both sites

[v] Data from Scott 2006 analyzed as a completely randomized design

na – Treatment not included at this site-year.

ns – F-test not significant at $p \leq 0.05$

* Significant at $p \leq 0.05$

APPENDIX H – SPATIAL COVARIANCE PARAMETER ESTIMATES AND MODEL FIT STATISTICS FOR PROC MIXED PROCEDURE USED FOR FIELD-SCALE TRIALS FROM CHAPTER FIVE

Table H.1 Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at BA 2005.

BA05	**Spatial Covariance Parameter Estimates**^{z}			
Variable Cov. Parameter	Subject	Estimate	Standard Error	P > Z
NDVI				
Spatial (pow)	Intercept	0.9524	0.0079	<0.001
Residual		0.0023	0.0002	<0.001

Type 3 Tests of Fixed Effects^{y}

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	3	208	1.36	0.256

Model Fit Criteria^{x}

Model	-2 Res Log Likelihood	AICC^{w}
Common Var.	-873.9	-869.8
Separate Var.	-870.3	-853.8
χ^2critical value^{v}	7.81	

Number of Observations^{u}

Treatment	FP	NR	SF	VRA
	73	23	77	91

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[z] Spatial covariance parameters estimated for the residual error of NDVI using SAS 9.1's (SAS Institute, Inc.) Proc Mixed procedure and the covariance test option (power structure)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), and variable rate (VRA)

Table H.2. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at BA 2005.

BA05 — **Spatial Covariance Parameter Estimates**[z]

Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
Yield				
Intercept				
Spatial (exp)	Farmer Practice	16.5	5.24	<0.001
Variance		75465	12848	<0.001
Spatial (exp)	Nitrogen Rich	24.04	14.59	0.050
Variance		100926	37849	0.004
Spatial (exp)	Split / Fixed	60.09	24.2	0.007
Variance		64708	20327	<0.001
Spatial (exp)	Variable Rate	28.6	7.65	<0.01
Variance		63926	11894	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	3	7.94	4.86	0.0332

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	3779.3	3783.3
Separate Var.	3738.2	3754.2
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	81	23	82	93

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), and variable rate (VRA)

Table H.3. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at NH 2005.

NH05 — **Spatial Covariance Parameter Estimates**[z]

Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
NDVI				
Intercept				
Spatial (pow)	Farmer Practice	0.983	0.0051	<0.001
Variance		0.00184	0.00046	<0.001
Spatial (pow)	Nitrogen Rich	0.983	0.0107	<0.001
Variance		0.001294	0.00066	0.024
Spatial (pow)	Split / Fixed	0.966	0.0092	<0.001
Variance		0.00260	0.00046	<0.001
Spatial (pow)	Variable Rate	0.980	0.0070	<0.001
Variance		0.00292	0.00070	<0.001
Spatial (pow)	Reduced	0.974	0.0070	<0.001
Variance	Nitrogen	0.00330	0.00068	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	4	7.97	15.77	<0.001

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	-1393.5	-1389.4
Separate Var.	-1425.0	-1404.4
χ^2critical value[v]	9.24	

Number of Observations[u]

Treatment	FP	NR	SF	VRA	RN
	103	26	91	96	89

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (power structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), variable rate (VRA), and Reduced Nitrogen (RN)

Table H.4. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at NH 2005.

NH05	Spatial Covariance Parameter Estimates[z]			
Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
Yield				
Intercept				
Spatial (exp)	Farmer Practice	72.7	24.77	0.002
Variance		36039	10376	<0.001
Spatial (exp)	Nitrogen Rich	97.2	75.88	0.100
Variance		105002	72449	0.074
Spatial (exp)	Split / Fixed	0.514	745.7	0.500
Variance		38060	5252.8	<0.001
Spatial (exp)	Variable Rate	67.3	25.7	0.004
Variance		34520	11034	<0.001
Spatial (exp)	Reduced	126.3	118.8	0.144
Variance	Nitrogen	89356	74675	0.116

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	4	1	2.22	0.461

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	5993.0	5997.0
Separate Var.	5852.8	5873.3
χ^2critical value[v]	9.24	

Number of Observations[u]

Treatment	FP	NR	SF	VRA	RN
	108	28	106	109	107

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), variable rate (VRA), and Reduced Nitrogen (RN)

Table H.5. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at VJ 2005.

VJ05	**Spatial Covariance Parameter Estimates**[z]			
Variable Cov. Parameter	Subject	Estimate	Standard Error	P > Z
NDVI				
Spatial (exp)	Intercept	16.0	2.77	<0.001
Residual		0.00098	0.000105	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	3	269	22.22	<0.001

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	-1281.0	-1277.0
Separate Var.	-1280.4	-1263.9
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	91	37	92	88

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (expontential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), and variable rate (VRA)

Table H.6. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at VJ 2005.

VJ05 — **Spatial Covariance Parameter Estimates**[z]

Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
Yield				
Intercept				
Spatial (exp)	Farmer Practice	29.0	10.1	<0.001
Variance		39118	8656	0.002
Spatial (exp)	Nitrogen Rich	0.757	13588	0.500
Variance		49533	10692	<0.001
Spatial (exp)	Split / Fixed	38.5	12.3	<0.001
Variance		66654	15901	<0.001
Spatial (exp)	Variable Rate	67.3	34.6	0.026
Variance		122661	50754	0.008

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	3	5.63	1.94	0.229

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	4126.9	4131.0
Separate Var.	4078.9	4095.0
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	73	43	95	93

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc [y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), and variable rate (VRA)

Table H.7. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at VS 2005.

VS05	**Spatial Covariance Parameter Estimates**^{z}			
Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
NDVI				
Intercept				
Spatial (exp)	Farmer Practice	62.4	32.7	0.028
Variance		0.00441	0.00178	0.009
Spatial (exp)	Nitrogen Rich	48.1	42.2	0.128
Variance		0.00093	0.00061	0.063
Spatial (exp)	Split / Fixed	14.1	5.56	0.006
Variance		0.00350	0.00062	<0.001
Spatial (exp)	Variable Rate	13.9	5.83	0.009
Variance		0.00304	0.00053	<0.001

Type 3 Tests of Fixed Effects^y

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	3	3.18	2.80	0.2021

Model Fit Criteria^x

Model	-2 Res Log Likelihood	AICC^w
Common Var.	-717.9	-713.9
Separate Var.	-733.9	-717.3
χ^2critical value^v	7.81	

Number of Observations^u

Treatment	FP	NR	SF	VRA
	18	74	71	75

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), and variable rate (VRA)

Table H.8. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at VS 2005.

VS05	**Spatial Covariance Parameter Estimates**[z]			
Variable Cov. Parameter	Subject	Estimate	Standard Error	P > Z
Yield				
Spatial (pow)	Intercept	28.25	6.30	<0.001
Residual		127191	22171	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	3	224	19.56	<0.001

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	3488.0	3482.5
Separate Var.	3490.9	3507.5
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	84	19	69	79

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), and variable rate (VRA)

Table H.9. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at BA 2006.

BA06	**Spatial Covariance Parameter Estimates**^{z}			
Variable Cov. Parameter	Subject	Estimate	Standard Error	P > Z
NDVI				
Spatial (exp)	Intercept	34.6	5.49	<0.001
Residual		0.00149	0.00018	<0.001

Type 3 Tests of Fixed Effects^y

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	4	405	16.2	<0.001

Model Fit Criteria^x

Model	-2 Res Log Likelihood	AICC^w
Common Var.	-1648.0	-1644.0
Separate Var.	-1591.0	-1570.4
χ^2critical value^v	9.24	

Number of Observations^u

Treatment	FP	NR	SF	VRA	RN
	79	79	92	80	82

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), variable rate (VRA), and Reduced Nitrogen (RN)

Table H.10. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at BA 2006.

BA06	**Spatial Covariance Parameter Estimates[z]**			
Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
Yield				
Intercept				
Spatial (exp)	Farmer Practice	39.2	13.0	0.001
Variance		138378	32026	<0.001
Spatial (exp)	Nitrogen Rich	68.3	24.1	0.002
Variance		88467	25429	<0.001
Spatial (exp)	Split / Fixed	39.7	12.0	<0.001
Variance		104112	21851	<0.001
Spatial (exp)	Variable Rate	55.3	20.1	0.003
Variance		122637	33593	<0.001
Spatial (exp)	Reduced	35.3	11.1	<0.001
Variance	Nitrogen	105547	22834	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	4	13.6	2.53	0.089

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	6098.3	6102.3
Separate Var.	6063.1	6083.7
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA	RN
	87	79	94	86	91

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF), variable rate (VRA), and Reduced Nitrogen (RN)

Table H.11. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at KS 2006.

KS06	**Spatial Covariance Parameter Estimates**[z]			
Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
NDVI				
Intercept				
Spatial (exp)	Farmer Practice	30.9	9.4	<0.001
Variance		0.00076	0.00016	<0.001
Spatial (exp)	Nitrogen Rich	91.0	48.2	0.029
Variance		0.00142	0.00065	0.015
Spatial (exp)	Split / Fixed	38.2	12.0	<0.001
Variance		0.00081	0.00019	<0.001
Spatial (exp)	Variable Rate	60.5	26.4	0.011
Variance		0.00144	0.00052	0.003

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	3	4.24	1.76	0.287

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	-1650.7	-1646.7
Separate Var.	-1764.1	-1747.7
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	93	101	95	94

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)

Table H.12. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at KS 2006.

KS06 **Spatial Covariance Parameter Estimates[z]**

Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
Yield				
Intercept				
Spatial (exp)	Farmer Practice	30.9	9.3	<0.001
Variance		64989	13800	<0.001
Spatial (exp)	Nitrogen Rich	26.3	7.1	<0.001
Variance		47062	8596	<0.001
Spatial (exp)	Split / Fixed	32.3	8.2	<0.001
Variance		80869	15881	<0.001
Spatial (exp)	Variable Rate	26.6	8.0	<0.001
Variance		121603	24350	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	3	15.6	3.28	0.049

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	5514.8	5518.9
Separate Var.	5429.9	5446.3
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	98	103	99	99

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Probabilities values less than or equal to 0.05 indicate that allowing separate variance estimates for each treatment resulted in a significantly improved model fit

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)

Table H.13. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at RE 2006.

RE06	**Spatial Covariance Parameter Estimates[z]**			
Variable Cov. Parameter	Subject	Estimate	Standard Error	P > Z
NDVI				
Spatial (pow)	Intercept	0.9784	0.00473	<0.001
Residual		0.00240	0.00044	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	3	386	11.22	<0.001

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	-1661.4	-1557.4
Separate Var.	-1551.9	-1535.5

χ^2critical value[v] 7.81

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	104	98	110	97

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (power structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)

Table H.14. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at RE 2006.

RE06	Spatial Covariance Parameter Estimates[z]			
Variable Cov. Parameter	Subject	Estimate	Standard Error	P > Z
Yield				
Spatial (exp)	Intercept	22.0	3.13	<0.001
Residual		179046	17552	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	3	386	1.24	0.293

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	5992.6	5996.6
Separate Var.	6065.8	6082.2
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	103	97	113	98

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)

Table H.15. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at RP 2006.

RP06	Spatial Covariance Parameter Estimates[z]			
Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
NDVI				
Intercept				
Spatial (exp)	Farmer Practice	107.2	39.9	0.004
Variance		0.00160	0.00049	<0.001
Spatial (exp)	Nitrogen Rich	55.1	17.0	<0.001
Variance		0.00130	0.00026	<0.001
Spatial (exp)	Split / Fixed	66.7	21.1	<0.001
Variance		0.00133	0.00030	<0.001
Spatial (exp)	Variable Rate	66.6	21.2	<0.001
Variance		0.00153	0.00034	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	3	8.9	4.07	0.045

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	-1911.6	-1907.5
Separate Var.	-1944.1	-1927.7
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	132	133	129	117

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)

Table H.16. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at RP 2006.

RP06	**Spatial Covariance Parameter Estimates**^{z}			
Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
Yield				
Intercept				
Spatial (exp)	Farmer Practice	60.3	15.2	<0.001
Variance		37012	7066.4	<0.001
Spatial (exp)	Nitrogen Rich	9.0	9.9	0.183
Variance		23306	3504.4	<0.001
Spatial (exp)	Split / Fixed	149.1	75.9	0.025
Variance		70914	31760	0.013
Spatial (exp)	Variable Rate	100.1	29.2	<0.001
Variance		35151	8698.3	<0.001

Type 3 Tests of Fixed Effects^y

Variable	Num. DF	Den. DF	F - value	P>F
Yield	3	5.45	3.22	0.112

Model Fit Criteria^x

Model	-2 Res Log Likelihood	AICC^w
Common Var.	6504.5	6508.5
Separate Var.	6423.7	6440.0
χ^2critical value^v	7.81	

Number of Observations^u

Treatment	FP	NR	SF	VRA
	129	128	132	118

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)

Table H.17. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola NDVI at VJ 2006.

VJ06 — **Spatial Covariance Parameter Estimates**[z]

Variable Cov. Parameter	Subject	Estimate	Standard Error	P > Z
NDVI				
Spatial (exp)	Intercept	22.1	3.06	<0.001
Residual		0.00131	0.00014	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
NDVI	3	340	0.51	0.675

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	-1557.9	-1553.9
Separate Var.	-1529.6	-1513.2
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	99	92	110	96

[z] Spatial covariance parameters estimated for the residual error of NDVI using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)

Table H.18. Covariance parameter estimates, F-test, model fit criteria, and number of observations per treatment for canola grain yield at VJ 2006.

VJ06 — **Spatial Covariance Parameter Estimates[z]**

Variable Subject Cov. Parameter	Treatment	Estimate	Standard Error	P > Z
Yield				
Intercept				
Spatial (exp)	Farmer Practice	20.7	5.9	<0.001
Variance		38570	6546	<0.001
Spatial (exp)	Nitrogen Rich	0.343	46.1	0.497
Variance		33167	5244	<0.001
Spatial (exp)	Split / Fixed	37.3	11.5	<0.001
Variance		53197	12149	<0.001
Spatial (exp)	Variable Rate	38.2	15.0	0.006
Variance		61215	16553	<0.001

Type 3 Tests of Fixed Effects[y]

Variable	Num. DF	Den. DF	F - value	P>F
Yield	3	10.3	2.58	0.110

Model Fit Criteria[x]

Model	-2 Res Log Likelihood	AICC[w]
Common Var.	4704.5	4708.5
Separate Var.	4687.7	4704.1
χ^2critical value[v]	7.81	

Number of Observations[u]

Treatment	FP	NR	SF	VRA
	91	81	102	81

[z] Spatial covariance parameters estimated for the residual error of grain yield using the covariance test option (exponential structure) of the Proc Mixed procedure in SAS 9.1 (SAS Institute, Inc.)

[y] F-test for the effects of N management treatment for the selected model

[x] Mixed analysis completed using both a common variance estimate and separate variance estimates (smaller is better for both model fit criteria)

[w] AICC–corrected Akaike information criterion

[v] Model with smaller -2 Res. Log Likelihood value is a significant improvement in the alternate model if the difference between 2 Res. Log Likelihood exceeds the critical χ^2 value

[u] Farmer Practice (FP), Nitrogen Rich (NR), Split/Fixed (SF) and Variable Rate (VRA)