Final Project Report
for the

SASKATCHEWAN CANOLA DEVELOPMENT COMMISSION

PROJECT TITLE: EVALUATING IN-SEASON YIELD POTENTIAL AND NITROGEN FERTILIZER REQUIREMENTS IN CANOLA USING THE GREENSEEKER™ SENSOR

(CARP SCDC 03/05-01)

2005 - 2007

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1.0 EXECUTIVE SUMMARY

The greatest challenge in N fertilizer management in Saskatchewan is determining rates at the time when most N fertilizer is applied that are appropriate for the specific soil and growing conditions. Optical sensors have potential as tools to help producers to better match N inputs with crop demands, thus resulting in enhanced nitrogen use-efficiency and economic returns. These sensors measure the crop's normalized difference vegetation index (NDVI), which is an indirect measure of biomass, N-uptake, and yield potential. Two separate studies were completed to: 1) develop the empirical equations required to estimate canola yield potential and N requirements using optical sensors and 2) to evaluate the feasibility of sensor-based N management for canola compared to other N management treatments including the current, conventional practice of using yield goals to determine N rates and banding the crop's entire N requirements at the time of seeding.

We developed the empirical equations using data from small plot experiments at Indian Head, Scott, Swift Current, Brandon, and Ottawa where N rates and seeding rates were varied to establish plots with a wide range of potential yields. We excluded data from Scott in 2005 because of severe hail and from Swift Current in 2006 and 2007 and Scott in 2007 because hot, dry growing conditions during flowering and pod-filling severely limited grain yields at these sites. To account for differences in crop growth from one site- year to the next, we divided NDVI by several potential normalizing values, including days from planting (DFP) and various types of heat units accumulated between seeding and sensing. The heat units that were tested included growing degree days (base temperatures of 0 ˚C (GDD_0) and 5 ˚C (GDD_5), corn-heat units (CHU) and physiological days (P-days). Overall, the equations developed using only the data from 2005 and 2006 had higher correlation coefficients (0.444-0.562) than when data from all three years were included (0.351-0.447). Despite the lower correlation coefficients, the equations developed using data from all three years were similar to those developed from the 2005-06 data, although slightly more conservative in their estimates of yield potential. Of all of the potential divisors tested, the best correlation resulted when NDVI was divided by CHU (R^2=0.447). With the exception of P-days being slightly poorer (R^2=0.363), all of the heat units performed similarly (R^2=0.437-0.447). Even though dividing NDVI by days from planting resulting in only a slight improvement over NDVI on its own, we recommend doing so when temperature data is not available.

Sensor-based N management (Variable Rate N – VRN) was evaluated at Indian Head and Scott in 2005-07 along with several other N management treatments including the predominant practice of banding the crop's entire N requirements beneath the soil surface at seeding (Farmer Practice N – FPN). For the VRN treatment, we banded 41-66% of the estimated N requirements at seeding time and determined topdressing rates during the bolting stage using optical sensors and high N reference plots. For the majority of the site-years, Indian Head in 2006 and to a lesser extent Scott in 2007 being the exceptions, sensor-based N management performed well relative to the other treatments. While the NDVI of the unfertilized check was always lower than the NDVI of the fertilized treatments, differences among the fertilized treatments tended to be

small. On average, we applied 28 kg N ha^{-1} less N for the VRN treatment than for the FPN treatments, and, with the exception of Indian Head in 2006, no differences in grain yield were observed between the two treatments. Due to the dry conditions during the flowering and pod-filling stages at Indian Head in 2006 there was no response to topdressed N. However, the yield of the FPN treatment, where an elevated rate of N was applied at seeding, was 380 kg ha^{-1} higher than the VRN treatments at this site-year. These results indicate that soil moisture conditions at the time of the N topdressing application should be taken into consideration along with optical sensor measurements when deciding whether or not to topdress N. Variability for the agronomic N-use efficiency (ANUE) measurements was high, thus no significant differences between the FPN and VRN treatments were detected. There was, however, an overall tendency for ANUE to be relatively low at the high N rates and the overall mean ANUE of the VRN treatments at Indian Head was 10.9 kg grain kg N^{-1} compared with 7.7 kg kg^{-1} for the FPN treatment. At Scott, where yields and the overall response to N was typically lower, the overall mean ANUE estimates were 4.3 kg kg^{-1} and 3.9 kg kg^{-1} for the VRN and FPN treatments respectively.

Sensor-based N management appears to be a feasible option for increasing the efficiency of N fertilizer for canola production in western Canada, especially in the Black soil zone. In the current economic environment, however, increased efficiency alone will not provide sufficient incentive for producers to adopt this technology. For the practice to be economically viable, the value of the yield gains and/or N fertilizer savings must be sufficiently large to cover the added cost of the extra field operation. Nonetheless, sensor-based N management appears to have potential for enhancing ANUE in canola production and, provided that the risks and benefits of benefits of sensor-based N management are managed appropriately, economic profitability for canola producers.

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2.0 OVERALL BACKGROUND AND OBJECTIVES

Nitrogen is the most limiting nutrient in most Saskatchewan soils and, aside from water availability, inadequate N fertility is the factor that most commonly limits grain yields in much of the Northern Great Plains. Consequently, more than N is applied as fertilizer than any other nutrient; in the 2002 crop year, nearly 1.3 million Mt of N fertilizer was applied in the Canadian Prairies (including northern British Columbia) compared with just over 0.2 million Mt of P (Korol 2002). Canola (*Brassica napus* L.) typically responds well to N fertilizer and new, high yielding cultivars require large quantities of N to reach maximum economic yields (Brandt et al. 2007). According to Manitoba Agriculture, Food, and Rural Initiatives, for every 1000 kg ha^{-1} of canola seed produced, a total of 64 kg N ha^{-1} is required, thus approximately 180 kg N ha^{-1} in total (soil N plus fertilizer N) is required to produce a 2800 kg ha^{-1} canola crop (Manitoba Agriculture, Food, and Rural Initiatives 2007). When soil N availability is limiting, canola respond to applications of N fertilizer through increased vegetative growth, branching, pods per plant, leaf area index, and seed yield (Hocking et al. 1997). Increasing the quantity of N applied typically results in increasing grain yields until a plateau is reached where further N inputs of N have no effect on grain yield. Fertilizer N application rates higher than the minimum rate required to achieve maximum yield result in reduced economic profits and N-use efficiency, along with increased potential for the N to be lost from the soil-crop system with negative environmental consequences.

The quantity of fertilizer N that a given crop requires depends on its yield potential, the soil's capacity to supply N, and the extent to which applied N is lost. Crops with higher yield potential require more N in total than crops with comparatively low yield potentials (Manitoba Agriculture, Food & Rural Initiatives 2007). Canola yield potential depends on many factors, including but not limited to genetics, plant populations (Brandt et al. 2007) and growing season temperatures and moisture availability (Brandt and MacGregor 1997). The soil's capacity to supply N depends on both the quantity of residual mineral N (NH_4^+ and NO_3^-) in the soil at start of the growing season along with any N mineralized from organic matter during the growing season. In order to minimize N losses, it is usually recommended to band N fertilizer beneath the soil surface as close to time of crop uptake as possible; however, weather and landscape position are also important, with the highest losses, especially for fall-applied N, occurring in depressional areas where moisture can accumulate (Tiessen et al. 2005). The difficulty in choosing optimal N rates is that yield potential, soil N availability, and N losses all tend to be variable across the landscape and from one year to the next.

In regions where moisture availability frequently becomes limiting during the growing season, splitting N fertilizer applications between seeding time and an in-crop topdressing applications is one potential way to more accurately match the total amount of N applied with crop demands (Lafond et al. 2008). Applying a portion the N at or before the time of seeding and postponing the remainder into the growing season allows producers to assess soil moisture conditions and yield potential partway through the season and decide whether or not to invest in additional N inputs. Research completed at Indian Head and Scott showed that while topdressing the entire quantity of recommended N fertilizer as surface dribble-banded urea ammonium nitrate (UAN) one month after seeding was feasible for canola in some years, doing resulted in yield losses of up to 40% in dry years (Holzapfel et al. 2007). These risks can reduced by banding a portion of the recommended N rate at the time of seeding to ensure adequate N fertility early in the season and in the case of dry late-season conditions which could result in the post-emergent N being stranded on the soil surface. When 50-66% of the recommended N rates were applied at seeding, canola yields could be maintained as long as the N was applied prior to the start of flowering (Lafond et al. 2008). There is potential for optical sensors such as the GreenSeeker™ (www.ntechindustries.com) to be used as tools to help producers decide whether or not topdressing N is warranted and, if so, how much additional N is required to optimize yields.

Active optical sensors emit specific bandwidths of visible and near infrared (NIR) light and measure the reflectance of the emitted light off of the crop canopy. In the case of the GreenSeeker™, the bandwidths are 671±6 nm (red) and 780±6 nm (NIR). The reflectance values are used to calculate the crop's normalized difference vegetation index (NDVI), which is an indirect measure of aboveground biomass, N uptake, and grain yield (Raun et al. 2001; Freeman et al. 2007). The current methods of estimating topdress N requirements using real-time NDVI measurements involve establishing high N reference areas in each field at the time of seeding and comparing the NDVI measurements from the crop being evaluated with those from the reference crop. Using previously established relationships between NDVI and grain yield, it is possible to use the measurements to estimate the yield potentials of the crops and, based on the difference between the two yield potentials, estimate how much additional N is required to achieve the maximum yield potential under the given environmental conditions (Raun et al. 2002). A unique attribute of the GreenSeeker™ sensing system is its ability to integrate with fertilizer application equipment in order to direct variable-rate fertilizer applications, in essence creating an N prescription map in real-time while the applicator is travelling through the field. This technology has potential to enhance the efficiency of N fertilizer in canola production and increase economic returns, provided that the reductions in N and/or increases in grain yield are sufficient to cover the cost of the topdressing application. Much of the previous research evaluating these methods has been completed with cereal crops such as winter wheat, wheat, and corn (Raun et al. 2002; Girma et al. 2006; Teal et al. 2006). Researchers at Oklahoma State University have played a central role in the development and extension of this technology and a wealth of additional information is available at their website (www.nue.okstate.edu). To the best of our knowledge, sensor-based N management has not yet been evaluated for canola and the empirical relationships required for estimating yield potential using NDVI have not yet been established for this crop.

The objectives of the current study were: 1) to investigate the potential for estimating canola yield potential using canopy NDVI measurements at an early enough growth stage to still reasonably expect a yield response to topdressed N and 2) to evaluate the feasibility of sensor-based N management relative to the current predominant practice of applying the entire quantity of recommended N as an in-soil band at the time of seeding.

3.0 STUDY DESCRIPTIONS & METHODOLOGY

3.1 Site Descriptions

Field experiments were completed at Agriculture and Agri-Food Canada locations at Indian Head and Scott, SK. Indian Head (53˚ 33.0’ N, 103˚ 39.0 W) is located in the thin Black Soil Zone and the soil is an Indian Head heavy clay (Rego Black Chernozem), while Scott (52˚ 21.6’ N, 108˚49.8 W) is in the moist Dark Brown Soil Zone and the soil is an Elstow loam (Orthic Dark Brown Chernozen). Indian Head receives an average of 335 mm of precipitation annually while an average of 269 mm is received at Scott. At 1.6 ˚C, the mean annual temperature at Scott is slightly cooler than Indian Head, which has a mean annual temperature of 2.6 ˚C. The two sites have 158 and 164 frost free days on average, respectively. For the first set of field experiments discussed in this report, trials were also completed all three years at Brandon, MB, Ottawa, ON, and Swift Current, SK. Results from these additional site-years, which were funded by AAFC’s Environmental Technology Assessment for Agriculture (ETAA) program, are included in the pertinent sections of this report.

3.2 Crop Management (All Experiments – Indian Head & Scott)

Selected agronomic information is summarized separately for each study in Tables 1 and 3. All of the field experiments were completed in fields that had been continuously cropped under no-till management for more than 15 years. Canola was seeded into standing cereal stubble in the oilseed phase of four-year cereal – pulse –

cereal – oilseed rotations and all sites received some form of a spring glyphosate application. For added weed control at Indian Head in 2006 and 2007, 1700 g trifluralin ha^{-1} was also applied in the fall.

We targeted early seeding and the actual seeding dates ranged from May 9 to May 19. Seeding was completed using two high clearance hoe press drills. 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 fertilizer was applied.

With the exception of N, all fertilizer formulations, application amounts, placement, and timing were the same for all of the treatments in both studies. At Indian Head in all three years, 40 kg P_2O_5 ha^{-1} in total 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 each year at Indian Head at 45 kg K_2O ha^{-1} and 15 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. In 2007 at Scott, the granular fertilizer blend had a guarantee of 5.5-25-25-8.5 and was seed placed at 56 and 67 kg ha^{-1} for the N rate by seed rate and sensor-based N management feasibility trials, respectively.

InVigor™ 5020, a glufosinate-ammonium tolerant hybrid, was the cultivar used at all site-years. Canola seed was treated with Prosper FL (120 g clothianidin L^{-1}, 56 g carbathiin L^{-1}, 120 g thiram L^{-1}, and 4 g metalaxyl L^{-1}), a systemic insecticide and fungicide. Competition from weeds during the growing season was controlled using recommended herbicides at the recommended rates and neither foliar fungicides nor insecticides were required. The spring glyphosate application did not provide adequate control of Canada thistle (*Cirsium avense)* at Indian Head in 2005, so we applied 196 g clopyralid ha^{-1} slightly before the recommended growth stage of growth stage 2.1 (Harper and Berkenkamp 1975; HB2.1. Aside from this, the only in-crop herbicides applied were 500 g glufosinate-ammonium ha^{-1} (plus 15 g clethodim ha^{-1} at Indian Head).

In both experiments, the number of established plants was determined for each plot when the canola was between HB2.2-2.6. Plant populations were measured by counting the number of plants in two to four 1 m rows and calculating the average number of plants m^{-2} for the plot. Sampling locations were selected randomly, however, the outside rows were not counted and no two counts from the same two rows were permitted.

The plots at Indian Head were swathed when approximately 60% of the seeds on the main raceme had turned colour and harvested using plot combines while at Scott the plots were straight-cut at maturity using plot combines. The harvested grain samples were then dried to constant moisture content, cleaned and weighed. Grain yields were adjusted to a seed moisture content of 10% and are reported in kg ha^{-1}.

3.3 Study #1: Estimating Canola Yield Potential from NDVI

The principal objective of this experiment was to determine whether it is possible to estimate the canola yield potential during the growing season using NDVI measurements. In developing the empirical NDVI-canola yield equation, data from Swift Current, Brandon, and Ottawa (2005-07) is included along with that from Indian Head and Scott. Agronomic data are presented for Indian Head and Scott only (Table 1).

The plots were arranged in a randomized complete block design (RCBD) with four replications at all site-years except for Ottawa in 2006 and 2007 where there were three replications. The treatments were a factorial combination of six levels of N fertilizer inputs (0, 25, 50, 100, 150, and 200 kg N ha^{-1}) and four levels of seed inputs (25, 50, 100, and 200 viable seeds m^{-2}). We varied the amounts of N fertilizer and seed in order to establish plots with a wide range of both early season canopy closure and grain yields. Seedling mortality can be high for canola and is often variable from one year to the next depending on soil conditions at seeding time (Brandt et al. 2007). Canola adapts to low plant populations with increased vegetative growth, however, full yield potentials are not always realized at reduced plant populations, especially when large amounts of N fertilizer are applied (Brandt et al. 2007). The Canola Council of Canada recommends targeting 75-150 plants m^{-2} and allowing for 50% seedling mortality when calculating the amount of seed to use. The effects that variability in plant populations will have on the NDVI-yield relationship are uncertain, however, because of the high levels of variability in canola establishment that often occur on a field-scale, our goal is to develop an equation that will apply across a broad range of canola plant populations.

At various times throughout each growing season, we measured the average NDVI of each plot using handheld GreenSeeker™ sensors. These sensors calculate NDVI according to Eq. 1.

$$NDVI = (NIR-red)/(NIR+red) \qquad [Eq. 1]$$

where NIR is the proportion of emitted NIR light that is reflected off of the crop canopy and red is the quantity of emitted visible red light that is reflected off of the crop canopy.

The frequency and timing of the sensor-measurements varied from one site-year to the next. All of the sensing dates along with the corresponding growth stages are presented with the results in Tables 11-14. The crop growth stages for the various sensing dates varied from the cotyledon stage to the late pod-filling stage and the critical period for estimating canola yield potential was between the 5-leaf stages to the onset of flowering (HB2.5-4.1). Previous research suggests that to minimize the risk of yield losses, N should not be topdressed later than the bolting stage (Lafond et al. 2008); however, preliminary data analysis indicated that we could not accurately estimate canola yield potential with NDVI measurements collected prior to HB2.5.

At the early flowering stage, the entire aboveground portions of the plants from two 0.5 m rows were removed to determine the above ground biomass production at this growth stage. Biomass samples were dried, weighed, and their converted to kg ha^{-1}.

Next, the entire dried samples were ground and analyzed for N content using the Kjeldahl method. Total N uptake (kg N ha^{-1}), excluding the N contained in the roots, was calculated for each plot by multiplying plant N content (g g^{-1}) by the corresponding biomass yield (kg ha^{-1}). Sampling dates for each of the site-year are presented with other selected agronomic information in Table 1.

Grain N content (g 1000 g^{-1}) was determined for each plot using the Kjeldahl method in all cases except for Scott in 2005 where an NIR instrument was used. The quantity of N harvested with the canola seed (kg N ha^{-1}) was calculated by multiplying grain N content (g g^{-1}) by the corresponding grain yield for each plot.

Fall residual NO_3-N was determined by collecting soil samples from the plots after harvest and analyzing them for NO_3-N concentrations. In 2005 at Indian Head, we sampled each plot to a depth of 60 cm. In 2006 and 2007 at Indian Head, we sampled fewer plots more intensively; collecting three cores from each of the plots where the amount of seed used was 100 seeds m^{-2} and submitted combined samples from each plot for the 0-60 cm and 60-120 cm soil depths. Each year at Scott, all plots were sampled to determine fall residual NO_3-N concentrations to a depth of 60 cm. All samples were collected from random locations within the plots.

Response data were analyzed separately for each of the six site-years using the GLM procedure of SAS 8.2 (SAS Institute, Inc.) and orthogonal contrasts were used to describe the various responses to the treatments. Prior to publishing the agronomic data from these experiments in peer-reviewed journals, the response data from Scott and Indian Head will be combined in a Mixed analysis (Littel et al. 1996) with that from Brandon, Swift Current, and Ottawa, at which point the SCDC will be fully acknowledged.

To establish whether or not it was possible to estimate canola yield during the growing season using NDVI, the data were arranged in a scatter plot using SigmaPlot 10 (Systat Software Ltd.) with the NDVI data on the *x* axis and grain yield on the *y* axis. Under the recommendation of Dr. Bill Raun at Oklahoma State University, the relationship between NDVI and grain yield was described using a two-parameter exponential equation (Bill Raun, personal communication). Additional evidence supporting the use of an exponential equation to correlate NDVI to crop parameters exists in the literature (Broge and Mortensen 2002).

We tested several potential values for normalizing NDVI to account for differences in growth rate between years and geographic locations. One of the challenges with using NDVI to estimate the yield potential of crops is that NDVI continually

Table 1. Selected agronomic information for N rate by seeding rate study with canola completed over three years at Indian and Scott.

Operation / Measurement	Indian Head 2005	Indian Head 2006	Indian Head 2007	Scott 2005	Scott 2006	Scott 2007
K_2SO_4[z] application date (rate)	April 28 90 kg ha^{-1}	October 26 (05) 90 kg ha^{-1}	May 9 90 kg ha^{-1}	n/a	n/a	n/a
Pre-emergent herbicide application	May 9 890 g ha^{-1} glyphosate	October 19 (05) 1700 g trifluralin May 16 440 g glyphosate ha^{-1}	October 19 (06) 1700 g trifluralin May 7 890 g ha^{-1} glyphosate	May 15 440 g glyphosate ha^{-1}	May 10 440 g glyphosate ha-^{1}	May 13 440 g glyphosate ha-^{1}
Seeding Date	May 11	May 15	May 9	May 19	May 18	May 12
Plant Count Date	June 13	June 20	June 12	June 8	June 12	June 5
In-Crop Herbicide	June 3 196 g ^{1} clopyralid ha^{-1} June 6 500 g glufosinate ammonium ha^{-1} + 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} plus 15 g clethodim ha^{-1}	June 16 500 g glufosinate ammonium ha^{-1}	June 13 500 g glufosinate ammonium ha^{-1}	June 9 500 g glufosinate ammonium ha^{-1}
Biomass Sample Date	July 11	July 6	July 12	July 19	June 30	June 27
Swathing Date	August 30	August 10	August 14	Straight-cut	Straight-cut	Straight-cut
Harvest Date	September 6	August 29	August 29	September 30	August 23	August 23
Fall Soil Sample Date	October 21	September 14	October 12	October 27	August 30	August 26

[z]0-0-50-17

changes over the course of the growing season. Consequently, dividing NDVI values by some factor that affects crop growth (such as time or temperature) can improve the correlation with grain yield when data from different years and/or geographic regions are combined. For winter wheat, Raun et al. (2002) recommended dividing NDVI by the number of days between planting and sensing to improve the relationship between NDVI and winter wheat yield while for corn, Teal et al. (2006) showed that dividing NDVI by growing degree days (GDD) was also effective for improving the relationship between NDVI and grain yield. Compared with using days, dividing NDVI by GDD increased the range of growth stages over which yield potential could be. The potential normalizing values evaluated were the number of days from planting to sensing as well as several different heat units including GDD (base temperatures of 0 ˚C [GDD_0] and 5 ˚C [GDD_5]), corn heat units (CHU), and physiological days (P-days).

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 2008). Eq. 2 was used to calculate GDD:

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

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. Eq. 3 was used to calculate daily CHU.

$$CHU = 0.9(T_{min}-4.4)+1.665(T_{max}-10)-0.042(T_{max}-10)^2 \qquad \text{[Eq. 3]}$$

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^{o}C, the optimum temperature is 17^{o}C and the maximum is 30^{o}C (Wilson 2002). Daily P-days were calculated using Eq. 4:

$$P\text{-}Days = 1/24 * [5 * P(T_1) + 8 * P(T_2) + 8 * P(T_3) + 3 * P(T_4)] \qquad \text{[Eq. 4]}$$

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 5 through 8 describe the P functions used to calculate P-days in this study:

$P = 0$	when T < 5˚ C	[Eq. 5]
$P = k * \{1 – [(T-5)^2 / (17-5)^2]\}$	when 7 <= T < 17˚ C	[Eq. 6]
$P = k * \{1 – [(T-17)^2 / (30-17)^2]\}$	when 17 <= T < 30 ˚ C	[Eq. 7]
$P = 0$	when T >= 30˚ C	[Eq. 8]

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

3.3 Study #2: Evaluating the Feasibility of Sensor-Based N Management

The objective of the second study was to examine the feasibility using optical sensors and reference strips where N is not limiting to determine N topdressing requirements relative to the conventional practice of applying the crop's entire estimated N requirements in the soil at the time of seeding. Several additional treatments were included to allow us to determine whether there was an overall response to N fertilizer, whether there was a response specifically to the topdressed N, and whether there were any yield losses (or gains) associated with applying N in a split application versus all at seeding. The treatments that were included along with the proportions of N applied at seeding and topdressed are presented in Table 2.

The following five treatments were included at all site-years: 1) an unfertilized check where no N fertilizer was applied, 2) N-Rich (NR), where N fertilizer was applied as urea at the time of seeding at amounts considered sufficient to ensure that N would not become limiting during the growing season, 3) Farmer Practice N (FPN), where all N fertilizer was applied as urea at the time of seeding at rates considered sufficient to support average yield goals 4) Split application / Fixed rate N (SFN), where 41-66% of N was applied as urea at the time of seeding and urea-ammonium nitrate (UAN) was surface dribble-banded in a topdressing application at the bolting stage to bring the total amount up to that of the FPN treatment and 5) Variable Rate N (VRN), where the same rate of urea was applied at seeding as for the SFN treatment and a variable rate of UAN was applied in-crop (HB3.1-4.1), with the rates determined using optical sensors and high-N reference plots. Each year at Indian Head, we also included a Reduced N (RRN) treatment where the same rate of urea was applied at seeding as in the SFN and VRN treatments but no further N was applied. The absolute quantities of N fertilizer applied in the various treatments varied between site-years and are presented along with the spring residual NO_3-N levels in Table 2. The dates of the topdressed N applications and other pertinent agronomic information appear in Table 3.

The N application algorithms used to determine N topdressing requirements in the VRN treatments were based on empirical yield potential curves developed using all of the data available at the time for each of the three years. For the yield potential curves used in this aspect of the research, we divided NDVI by the GDD (base temperature 0˚ C) accumulated between seeding and sensing. In 2005, the actual best-fit curve was adjusted upwards by 33% under the assumption that a crop's yield potential during the growing season is often higher than the grain yields that are realized (William R. Raun, personal communication). In 2006 and 2007, we tested two variations of the N application algorithm which used slightly different variations of the empirical equation to estimate yield potential. In the variation hereafter referred to as VRN1, we used the actual best-fit yield potential curve with no upward adjustment, while in the treatment hereafter referred to as VRN2 we estimated canola yield potential using the adjusted curve. With all other factors being equal, the net effect of adjusting the yield potential curves upwards was to increase the recommended N rates by the same percentage as the curves were increased, 33% in the current case. In 2005, we calculated the equations using Excel 2000 (Microsoft Corporation) and in 2006-07, we used SigmaPlot 2000 (Systat Software, Inc.). The five equations that were used to estimate yield potential over the course of the study are presented graphically in Fig. 1.

Table 2. Residual NO_3-N prior to seeding and applied fertilizer rates (kg N ha^{-1}) for canola at Indian Head and Scott in 2005, 2006, and 2007.

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	FPN[w]	48	100	0	100
		NR[w]		200	0	200
		Split[w]		41	60	101
	2006	FPN	43	106	0	106
		NR		191	0	191
		Split		48	34[v]	82[v]
	2007	FPN	34	100	0	100
		NR		150	0	150
		Split		66	34	100
Scott	2005	FPN	34	116	0	116
		NR		216	0	216
		Split		56	60	116
	2006	FPN	40	103	0	103
		NR		163	0	163
		Split		69	34	103
	2007	FPN	45	100	0	100
		NR		66	34	100
		Split		160	0	160

[z]Quantity of fertilizer N supplied at seeding as mid-row banded granular urea
[y]Quantity of fertilizer N supplied topdressed as surface dribble banded urea ammonium nitrate (UAN)
[x]Total quantity of fertilizer N applied
[w]FPN – Farmer Practice; NR – Nitrogen rich; Split - all treatments that received split or reduced applications of fertilizer N (SFN, VRN, and RRN). Topdressed N amounts apply only to the SFN treatment.
[v]SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment

Table 3. Selected agronomic information for sensor-based N management feasibility study with canola completed over three years at Indian and Scott.

	Indian Head			Scott		
Operation / Measurement	2005	2006	2007	2005	2006	2007
K_2SO_4[z] application date (rate)	April 28 (90 kg ha^{-1})	October 26 (05) (90 kg ha^{-1})	May 9 (90 kg ha^{-1})	n/a	n/a	n/a
Pre-emergent herbicide application	May 9 890 g ha^{-1} glyphosate	October 19 (05) 1700 g trifluralin May 16 440 g glyphosate ha^{-1}	October 19 (06) 1700 g trifluralin May 7 890 g ha^{-1} glyphosate	May 15 440 g glyphosate ha^{-1}	May 10 440 g glyphosate ha-^{1}	May 13 440 g glyphosate ha-^{1}
Seeding Date	May 11	May 15	May 9	May 19	May 18	May 15
Plant Count Date	June 13	June 20	June 12	June 15	June 12	June 5
In-Crop Herbicide	June 3 196 g ^{1} clopyralid ha^{-1} June 6 500 g glufosinate ammonium ha^{-1} + 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} plus 15 g clethodim ha^{-1}	June 16 500 g glufosinate ammonium ha^{-1}	June 13 500 g glufosinate ammonium ha^{-1}	June 9 500 g glufosinate ammonium ha^{-1}
NDVI measurement date	June 23	June 25	June 26	June 24	June 28	June 27
PE N application date	June 24	June 29	June 27	June 27	June 30	June 27
Swathing Date	August 30	August 10	August 10	Straight-cut	Straight-cut	Straight-cut
Harvest Date	September 6	August 29	August 29	September 30	August 23	August 23
Fall Soil Sample Date	October 21	September 14	October 12	October 27	August 30	August 26

[z]0-0-50-17
na – not applicable

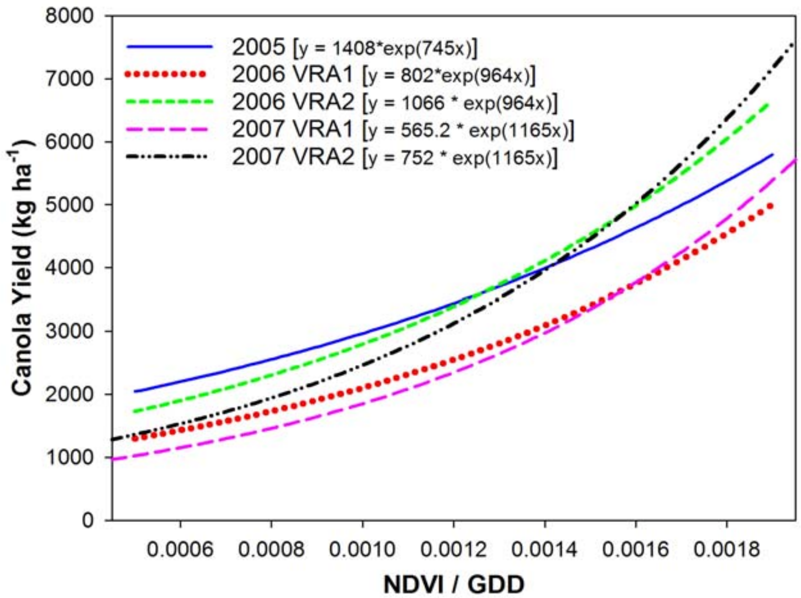

Figure 1. Empirical equations used to estimate canola yield potential in sensor-based N management feasibility study. Growing degree days (GDD) are calculated using a base temperature of 0 ºC.

The quantities of N topdressed in the VRN treatments were based on the estimated yield potentials of both the crop being assessed and the high N reference crop. Equation 9 was used to calculate the post-emergent N rates from the estimated yield potentials of the NR and VRN treatments.

$$N_{REQ} = (N_{NRICH} - N_{NLTD}) / E \qquad \text{[Eq. 9]}$$

where N_{REQ} is the recommended quantity of N to be topdressed; N_{NRICH} is the quantity of N removed in the grain of the high N reference crop at its estimated yield potential; N_{NLTD} is the quantity of N removed in the grain the of crop under evaluation at its estimated yield potential; and E is an efficiency factor which was set to a value of 0.5. To estimate the quantity of N removed in the canola seed, a grain N concentration of 33 g N kg grain^{-1} was assumed.

Grain N concentrations were determined using the Kjeldahl method at Indian Head in 2005 and Scott in 2006. At Scott in 2005, grain N was determined using an NIR instrument (Daun et al. 1994) and a LECO protein analyzer (Dumas method) was used at Indian Head in 2006 and 2007. A factor of 6.25 was used to convert protein concentrations to grain N concentrations at Scott in 2005 (Williams et al. 1998). Grain N concentrations (kg kg^{-1}) were multiplied by the grain yields (kg ha^{-1}) to calculate the grain N yields (kg N ha^{-1}).

Each year following harvest, soil samples were collected from each plot to a depth of 60 cm and analyzed for residual NO_3-N. In 2005 at Indian Head, we collected one soil sample from each plot, while in 2006 and 2007 we combined three separate soil cores from each plot into a composite sample for zero to 60 cm profile only. At Scott in all three years, two soil samples from each plot were combined and analyzed for NO_3-N concentrations. All soil samples were collected from random locations within each plot.

Agronomic nitrogen use-efficiency (ANUE) was calculated for each fertilized plot using Eq. 10 (Fageria and Baligar 2003; Fageria and Baligar 2005).

$$ANUE = (Y_{FERT} - Y_{CHECK}) / N_{APPLIED} \quad \text{[Eq. 10]}$$

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 N ha^{-1}). Agronomic NUE is expressed as kg grain yield kg N $applied^{-1}$.

All response data were analyzed separately for each site-year using the general linear model (GLM) procedure of SAS 8.2 (SAS Institute Inc.). The Ryan-Einot-Gabriel-Welsch multiple range test, which controls the Type I experiment-wise error, was used for mean separations. Linear contrasts were used to compare the NR and FPN treatments to the combined split treatments (SFN, VRN, and RRN) and to compare the two variations of the VRN treatment combined (VRN1 and VRN2; 2006 and 2007 only) to each of the other fertilized treatments on their own. All treatments were included in the analyses of all response variables with the exception of ANUE, where the unfertilized check was excluded. Differences between treatments were declared significant at the 5% probability level.

4.0 RESULTS & DISCUSSION

4.1 Growing Season Weather Conditions

Early spring moisture conditions were considered adequate to excellent at Indian Head for all three years (Table 4). At Scott, initial soil moisture conditions were relatively low in 2005 and 2007, but considerably higher in 2006. Note that the soil was sampled to a depth of 90 cm at Scott compared with 120 cm at Indian Head. So that spring soil moisture availability can be compared between the two sites, total moisture levels in Table 4 are expressed as volumetric soil water content in addition to water depth.

Growing season temperatures and precipitation levels for the 2005-07 growing seasons at Indian Head and Scott are presented in Tables 5 and 6, respectively. Overall, conditions at Indian Head were cool and wet in 2005 and were conducive to high canola yields. Growing season temperatures in 2006 at Indian Head were closer to normal; however, the last significant rainfall event occurred on June 24 (data not shown) and conditions became very dry late in the season. In 2007 at Indian Head, temperatures were slightly below average overall; however, July was 1.5 ºC warmer than average. Indian Head received light hail accompanied by high wind speeds on June 21, 2007 and slight (<5%) physical damage to the pods was noted. Temperatures at Scott during the 2005 growing season were slightly cooler than the long-term average, mostly because of below normal temperatures from June through August. Similar to Indian Head, conditions in 2005 at Scott were cool and wet. Severe hail damaged the plots in mid-July with initial damage estimates for the area ranging from 60-85%; however the warm, moist conditions late in the season allowed the plants to recover well. Temperatures and precipitation at Scott in 2006 were close to normal overall, though July was hot and dry. Again in 2006, the plots at Scott were damaged by hail, with yield losses estimated at approximately 30% and considered evenly distributed across the plots. In 2007 at Scott, temperatures and precipitation from April through June were close to normal and slightly above normal respectively; however, as at Indian Head, July was hot and dry.

Table 4. Total spring soil moisture depth at Indian Head and Scott for 2005-07. Values in the brackets reported along with the total soil moisture levels are volumetric water concentrations.

	Indian Head			Scott		
	2005	**2006**	**2007[x]**	**2005**	**2006**	**2007**
Soil profile (cm)	spring soil moisture (mm) [z]					
0 – 60	155	236	212	111	190	141.1
60 – 120 (90 [y])	214	253	156	36	116	57.2
Total	**369 (31%)**	**489 (41%)**	**368 (31%)**	**147 (16%)**	**306 (34%)**	**198 (22%)**

[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
[x]Spring soil moisture estimated based on measurements from an adjacent study approximately 100 m away

Table 5. Mean monthly temperatures 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**	**2007**	**LT[z]**	**2005**	**2006**	**2007**	**LT[z]**
	mean monthly temperature (ºC)							
April	5.5	7.3	3.4	4.0	5.8	7.1	3.6	3.6
May	8.7	11.2	10.7	11.4	9.2	10.9	10.4	10.9
June	14.8	16.0	15.0	16.1	13.4	15.3	14.1	15.2
July	16.9	17.9	19.9	18.4	16.2	18.8	20.4	17.0
August	15.6	17.3	15.5	17.5	13.5	16.8	14.7	16.3
Average	**12.3**	**13.9**	**12.9**	**13.5**	**11.6**	**13.8**	**12.6**	**12.6**

[z]Long-term averages according to Environment Canada's Canadian Climate Normals (1971-2000; Environment Canada 2008)

Table 6. Total monthly precipitation levels 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**	**2007**	**LT[z]**	**2005**	**2006**	**2007**	**LT[z]**
	precipitation (mm)							
April	6.8	73.2	16.9	24.6	27.4	32.0	10.9	23.6
May	57.6	39.0	80.6	55.7	41.4	62.8	82.0	35.9
June	99.2	80.4	46.6	78.9	100.0	66.8	102.6	62.5
July	59.2	5.6	51.4	67.1	76.8	34.6	14.0	70.9
August	98.0	11.8	63.6	52.7	88.6	47.0	41.6	43.1
Total	**321**	**210**	**259.1**	**279**	**334**	**243**	**251.1**	**236**

[z]Long-term averages according to Environment Canada's Canadian Climate Normals (1971-2000; Environment Canada 2008)

4.2 Study #1: Estimating Canola Yield Potential using Optical Sensors

For study #1, which aimed to develop the empirical equations required to estimate canola yield potential using NDVI measurements, response data are presented for the trials at Indian Head and Scott only (Sections 4.2.1-4.2.3). Except in the cases where a significant N level by seed level interaction occurred, results are reported only for the main effects. Data from the additional locations (Brandon, Ottawa, and Swift Current) is included in sections 4.2.4 and 4.2.5, which look at the NDVI-yield relationships.

4.2.1. Crop Establishment

Nitrogen rate affected plant densities at Indian Head in 2007 and Scott in 2007, but neither site in 2005 or 2006 (Table 7). At Indian Head in 2007, plant densities increased quadratically, with an average of 74 plants m^{-2} at 100 kg N ha^{-1} and 60-63 plants m^{-2} observed at all other N rates. The reasons for the difference are unclear and that the F-test for the effect of N rate was not significant suggests that the higher densities observed when 100 kg N ha^{-1} was applied may have been due to chance. At Scott in 2007, there was a significant N level by seed level interaction (Table 7) for plant density whereby N rate only affected plant populations at the two highest seeding rates (Table 8). The observed results did not suggest NH_3 toxicity as the number of plants increased with N rate in a cubic / linear manner. This along with the fact that N level did not affect plant densities at the remaining four site-years indicates that NH_3 toxicity was not considered a confounding factor at the high N rates.

As expected, the number of established plants increased with increasing seeding rate at all site-years. The number of plants m^{-2} observed increased linearly with increasing seed levels at all site-years and densities ranged from 17-162 plants m^{-2}. At Indian Head in 2006, the quadratic and cubic contrasts were also significant, with the greatest increase in plants observed when the seeding rate was increased from 50 to 100 viable seeds m^{-2} and only a small increase observed when the number of viable seeds planted was increased from 100 seeds m^{-2} to 200 seeds m^{-2}. At Scott in 2007, plant densities increased linearly with the level of seed inputs at all N rates and quadratically at the 25, 50, and 100 kg ha^{-1} N levels. Note that seed level was excluded from the model at Scott in 2005; the reason being that an error at the time of seeding resulted in ten times the targeted number of viable seeds being planted at all rates.

Table 7. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on canola plant densities.

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level	plants m^{-2}					
0 kg N ha^{-1}	81	67	60	n/a	52	80
25 kg N ha^{-1}	87	59	62	n/a	57	86
50 kg N ha^{-1}	90	59	61	n/a	56	82
100 kg N ha^{-1}	77	58	74	n/a	53	95
150 kg N ha^{-1}	85	58	63	n/a	56	80
200 kg N ha^{-1}	92	64	61	n/a	50	90
Seed Level						
25 seeds m^{-2}	41d	24c	17d	n/a	21c	29
50 seeds m^{-2}	66c	38b	32c	n/a	32c	53
100 seeds m^{-2}	89b	92a	73b	n/a	56b	99
200 seeds m^{-2}	145a	98a	131a	n/a	106a	162
	ANOVA					
Source	p-values					
N-Level	ns	ns	ns	n/a	ns	*
Seed-Level	**	**	**	n/a	**	**
N*Seed	ns	ns	ns	n/a	ns	**
Replicate	ns	ns	ns	n/a	ns	**
Res. C.V.	20.4	26.8	24.3	n/a	31.9	16.8
Contrast						
N-Lin.	ns	ns	ns	n/a	ns	-
N-Quad.	ns	ns	*	n/a	ns	-
N-Cub.	ns	ns	ns	n/a	ns	-
Seed-Lin.	**	**	**	n/a	**	-
Seed-Quad	ns	**	ns	n/a	ns	-
Seed-Cub.	ns	**	ns	n/a	ns	-

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

Table 8. Mean plant densities and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Scott 2007.

SCOTT 2007							
Nitrogen Rate kg N ha^{-1}	Seeding Rates viable seeds m^{-2} 25	50	100	200	Orthogonal Contrasts lin.	quad.	cub.
	plants m^{-2}						
0	37	53	87	144	**	ns	ns
25	32	54	107	153	**	*	ns
50	25	47	100	155	**	*	ns
100	26	54	115	187	**	*	ns
150	29	57	86	147	**	ns	ns
200	23	55	97	185	**	ns	ns
Orthogonal Contrasts							
lin.	ns	ns	ns	**			
quad.	ns	ns	ns	ns			
cub.	ns	ns	*	*			

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

4.2.2 Biomass Yield and Total N-Uptake at Flowering

Above-ground biomass measurements were collected when the canola was at the early flowering stage. The F-test for the main effects of N fertilizer level on biomass yield was significant at all site-years. At Scott in 2006 the F-test for the main effect of seed input level was also significant and at Scott in 2007 there was a significant interaction between the two variables (Table 9).

For the site-years where the main effect of N fertilizer level was significant, biomass yields increased both linearly and quadratically with increasing amounts of N fertilizer and, at Indian Head in 2005, the cubic orthogonal contrast was also significant. For these site-years, biomass yields generally peaked when 100-150 kg N ha^{-1} was applied, with the exception being Indian Head in 2006 where the biomass yield observed at the highest N fertilizer level was significantly higher than for the 150 kg N ha^{-1} level but not the 100 kg N ha^{-1} level. At Scott in 2007, biomass yields increased with N at all seeding rates; however the shape of the response differed depending on the seed input level (Table 10). At 25, 100, and 200 seeds m^{-2}, biomass yields increased linearly with N level while the increase was quadratic at the 50 seeds m^{-2} level. At 200 seeds m^{-2}, the quadratic and cubic contrasts were also significant. On average, biomass yields of the unfertilized checks were 44-58% of those at the highest yielding N fertilizer level.

Table 9. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on canola biomass yields.

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level			kg ha^{-1}			
0 kg N ha^{-1}	2485d	2177c	3248b	3347d	1074b	1138
25 kg N ha^{-1}	3679c	3097bc	4303ab	4549c	1651a	1615
50 kg N ha^{-1}	4497bc	3961ab	4675ab	5208bc	1738a	1734
100 kg N ha^{-1}	4955ab	4357ab	5899a	6459a	1753a	1916
150 kg N ha^{-1}	4404bc	4594a	5014ab	6206ab	1843a	2000
200 kg N ha^{-1}	5601a	3939ab	5712a	6042ab	1671a	2211
Seed Level						
25 seeds m^{-2}	4653	3934	4548	n/a	1141c	1317
50 seeds m^{-2}	4215	3858	4706	n/a	1494b	1563
100 seeds m^{-2}	4255	3766	5189	n/a	1829a	2036
200 seeds m^{-2}	3957	3192	4972	n/a	2023a	2160
				ANOVA		
Source				p-values		
N-Level	**	**	**	**	**	*
Seed-Level	ns	ns	ns	n/a	**	**
N*Seed	ns	ns	ns	n/a	ns	**
Replicate	ns	ns	ns	ns	ns	**
Res. C.V.	23.7	36.3	39.2	21.7	29.8	16.8
Contrast						
N-Lin.	**	**	**	**	**	-
N-Quad.	**	**	*	**	**	-
N-Cub.	**	ns	ns	ns	ns	-
Seed-Lin.	*	*	ns	n/a	**	-
Seed-Quad	ns	ns	ns	n/a	**	-
Seed-Cub.	ns	ns	ns	n/a	ns	-

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

Although the F-tests were not significant, biomass yields decreased linearly with increasing seed input levels at Indian Head in 2005 and 2006, but not in 2007 (Table 9). The opposite was true at Scott in 2006 were biomass yields increased both linearly and quadratically with increasing seed input levels. The decrease in biomass yields with increasing seeds m^{-2} was attributed to a greater percentage of the planted seeds becoming established and much larger plants at the low seed input levels. McGregor (1987) found that that individual canola plants at densities of 4-7 m^{-2} grew approximately four times larger in mass that plants growing at densities of 186-200 plants m^{-2}. At Scott in 2007, where there was a significant N level by seed level interaction, seed input level did not affect biomass yields when no N was applied; however, increasing the amount of N applied resulted in a linear increase in biomass when N was applied, regardless of the rate (Table 10). In addition, the quadratic response was significant for the 25 and 150 kg ha^{-1} seed input levels and the cubic contrast was significant when 200 kg N ha^{-1} was applied. The underlying causes of the divergent results observed for the two locations are not certain, and our contrast to those reported by Brandt et al. (2007), who observed no effects of seeding rate on canola biomass yields over the course of eight site-years.

Table 10. Canola biomass yields and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Scott in 2007.

	SCOTT 2007						
Nitrogen Rate	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
	kg biomass ha^{-1}						
0	1005	1182	1142	1221	ns	ns	ns
25	1162	1458	2009	1832	*	*	ns
50	1143	1478	1832	2482	**	ns	ns
100	1281	1891	2147	2344	**	ns	ns
150	1340	1812	2541	2305	**	**	ns
200	1970	1556	2541	2778	**	ns	**
Orthogonal Contrasts							
lin.	**	ns	**	**			
quad.	ns	*	ns	*			
cub.	ns	ns	ns	**			

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

A significant N fertilizer level by seed input level interaction was observed for whole plant N concentrations (g kg^{-1}) at the early flowering stage in all three years at Indian Head (Table 11). At Scott, the F-test for the effects of N rate on plant N concentrations was significant in 2005 and both N rate and seeding rate affected plant N in 2006. There was no interaction between N fertilizer and seed input levels for plant N concentrations at Scott in 2005 or 2006, but an interaction occurred in 2007.

At Scott in 2005 and 2006, increasing the amount of N applied caused plant N concentrations to increase linearly and linear/quadratically, respectively (Table 11). At Indian Head in all three years and Scott in 2007, the N fertilizer level by seed input level interaction was significant in all three years, indicating that the effects of N fertilizer level on total plant N concentrations varied depending on the seeding rate used and vice versa (Tables 12-14). In all three years at Indian Head and at Scott in 2007, plant N concentrations increased linearly with increasing N fertilizer levels at all seed input levels. The cubic orthogonal contrast was also frequently significant, whereby N concentrations did not increase with increasing N at low N levels, increased more rapidly at intermediate N fertility, and then level off again at the highest N input levels. In a few instances, particularly at the low seeding rates, plant N concentrations decreased slightly with the addition of 25 kg N ha^{-1} relative to the unfertilized treatment, presumably due to the N becoming diluted in the plant as a result of the observed increase in biomass production. Other studies have also shown that canola whole plant N concentrations can sometimes decrease when small amounts of N are applied (Chamorro et al. 2002); however, increasing N concentrations as the amount of N applied was increased was the expected response (Chamorro et al. 2002; Hocking et al. 2002).

Table 11. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on whole plant N concentrations at the early flowering stage.

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level			g kg^{-1}			
0 kg N ha^{-1}	22.2	24.8	19.8	15.5c	31.3d	34.9
25 kg N ha^{-1}	23.2	23.4	20.3	15.4c	35.4c	35.8
50 kg N ha^{-1}	22.8	26.3	21.1	15.8c	38.5bc	38.4
100 kg N ha^{-1}	29.9	34.3	26.3	18.9b	41.1ab	45.7
150 kg N ha^{-1}	33.0	36.6	29.5	20.6ab	43.4a	46.2
200 kg N ha^{-1}	34.3	38.4	27.8	21.7a	43.4a	45.3
Seed Level						
25 seeds m^{-2}	29.5	34.5	27.9	n/a	40.9a	43.3
50 seeds m^{-2}	28.7	32.7	25.0	n/a	41.3a	41.8
100 seeds m^{-2}	26.7	27.9	22.7	n/a	37.4b	39.8
200 seeds m^{-2}	25.3	27.4	21.0	n/a	35.8b	39.3
			ANOVA			
Source			p-values			
N-Level	**	**	**	**	**	**
Seed-Level	**	**	**	n/a	**	**
N*Seed	*	*	*	n/a	ns	*
Replicate	ns	*	ns	**	*	ns
Res. C.V.	7.9	6.9	15.1	11.3	9.8	8.3
Contrast						
N-Lin.	-	-	-	**	**	-
N-Quad.	-	-	-	ns	**	-
N-Cub.	-	-	-	*	ns	-
Seed-Lin.	-	-	-	n/a	**	-
Seed-Quad	-	-	-	n/a	ns	-
Seed-Cub.	-	-	-	n/a	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 Scott in 2006, plant N concentrations decreased linearly with increasing levels of seed inputs and no interaction between the amount of N applied and seeds m^{-2} planted was observed, (Table 11). While evidence of such was not found in the literature, this observation was presumably a result of increased competition among the plants for the available soil N at the higher seed input levels. At Indian Head, an interaction between N fertilizer and seed input levels was observed whereby the inverse relationship between plant N concentrations and seeding rates was not always observed at all N fertilizer levels, however, there were no consistent patterns observed among the three years. In most cases at Indian Head, however, plant N concentrations decreased linearly with increasing seed inputs (Tables 12-14) and the overall trend was the same (Table 11). As at Scott in 2006, this negative response to seeding rate was attributed to increased intra-species competition for nutrients between the individual canola plants.

Table 12. Mean whole plant N concentrations 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	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
kg N ha^{-1}	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 13. Mean whole plant N concentrations 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	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
kg N ha^{-1}	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; *significant at 0.01 ≤ p ≤ 0.05; ** significant at p ≤ 0.01

At Scott in 2006, plant N concentrations decreased linearly with increasing seeding rate and no interaction between N and seeding rate was observed, (Table 11). While no seeding rate studies were found in the literature where whole plant N content was measured, this observation was presumably a result of increased levels of competition among the canola plants for the available soil N. At Indian Head, an N rate by seeding rate interaction was observed, the inverse relationship between plant N concentrations and seeding rates was not always observed at all N fertilizer rates, however, there were no consistent patterns observed among the three years. In most cases at Indian Head and at Scott in 2007; however, plant N concentrations decreased linearly with increasing seed inputs (Tables 12-14) and the overall trend was for N concentrations to decrease with increasing seed level (Table 11). As at Scott in 2006, the negative response of plant N concentrations to increasing seed inputs was attributed to increased intra-species competition for nutrients between the individual canola plants.

Table 14. Mean whole plant N concentrations and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Indian Head 2007.

	INDIAN HEAD 2007						
Nitrogen Rate	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
	g N kg $biomass^{-1}$						
0	28.2	17.4	18.1	15.8	**	*	**
25	20.9	21.0	21.0	18.5	ns	ns	ns
50	23.0	21.5	20.4	19.4	ns	ns	ns
100	31.7	30.4	23.4	19.7	**	ns	ns
150	34.2	30.4	28.1	25.6	**	ns	ns
200	29.3	29.3	25.6	27.0	ns	ns	ns
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	ns	**	ns	ns			
cub.	**	ns	ns	ns			

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

Table 15. Mean whole plant N concentrations (g N kg biomass^{-1}) and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Scott 2007.

	SCOTT 2007						
	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
Nitrogen Rate kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
	g N kg biomass^{-1}						
0	36.6	34.4	35.3	33.2	ns	ns	ns
25	39.1	37.7	34.2	32.2	**	ns	ns
50	44.1	39.0	36.9	33.8	**	ns	ns
100	47.5	47.3	44.5	43.4	ns	*	ns
150	47.5	49.4	41.5	46.3	ns	ns	*
200	45.2	43.2	46.2	46.9	ns	ns	ns
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	**	**	ns	ns			
cub.	ns	*	ns	*			

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

Nitrogen uptake of canola at the early flowering stage (HB4.1-4.2) varied depending on the treatment and site-year; with greatest overall uptake at Indian Head in 2005 (overall mean of 121 kg N ha^{-1}) and the lowest at Scott in 2006 (overall mean of 37 kg N ha^{-1}). The difference in N uptake between these two site-years was attributed to large differences in biomass yields (Table 9), as overall plant N concentrations were higher at Scott in 2006 than they were at Indian Head in 2005 (Table 11). The main effects for both N fertilizer and seed input levels on whole plant N uptake were significant at all site years except for Indian Head in 2007, where only the effect of N fertilizer level was significant (Table 15). At Scott in 2007, while the general trend was for whole plant N uptake to increase with increasing levels of both N fertilizer and seed inputs, there was a significant interaction between the two input levels (Table 16).

In 2005 and 2006 at Indian Head, N uptake decreased linearly with increasing seeding rate and in the 2007 and the response was linear/quadratic, with the greatest decrease in N uptake observed when the seeding rate was increased from 100 to 200 seeds m^{-2}. At Indian Head, N uptake at the 25 seeds m^{-2} seed input level ranged from 22-55% higher than for the 200 seeds m^{-2} level. The negative effect of seeding rate on plant N uptake is attributable to a combination of lower biomass yields and lower plant N concentrations at the higher seeding rates. In contrast, N uptake increased with increasing seeding rates at Scott in 2006, which was the driest of the site-years. The observed response was linear and quadratic, with the greatest increase observed when the seeding rate was increased from 100 to 200 seeds m^{-2}. However, whole plant N uptake was very low overall at Scott and the observed differences, although significant in certain cases, were small.

Table 16. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on total N uptake at the early flowering stage (kg N ha^{-1}).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level			kg N ha^{-1}			
0 kg N ha^{-1}	55.1d	54.5c	66.1b	52.4c	28.4b	39.5
25 kg N ha^{-1}	85.2c	72.4bc	87.6b	70.3bc	29.6b	57.0
50 kg N ha^{-1}	103.5c	106.0b	99.9b	83.0b	32.0b	64.9
100 kg N ha^{-1}	147.5b	147.6a	149.0a	121.5a	42.0a	86.9
150 kg N ha^{-1}	145.3b	151.2a	141.7a	127.1a	42.3a	91.5
200 kg N ha^{-1}	190.6a	165.2a	156.7a	131.9a	45.0a	101.3
Seed Level						
25 seeds m^{-2}	139.8a	139.6a	123.7	n/a	34.9b	57.5
50 seeds m^{-2}	124.3ab	127.2ab	121.5	n/a	35.3b	67.2
100 seeds m^{-2}	117.6bc	109.5bc	120.4	n/a	35.8ab	82.5
200 seeds m^{-2}	103.1c	89.8c	101.6	n/a	40.2a	86.9
			ANOVA			
Source			p-values			
N-Level	**	**	**	**	**	**
Seed-Level	**	**	ns	n/a	*	**
N*Seed	ns	ns	ns	n/a	ns	*
Replicate	ns	ns	ns	ns	**	**
Res. C.V.	23.7	36.8	39.3	25.1	19.1	23.5
Contrast						
N-Lin.	**	**	**	**	**	-
N-Quad.	ns	**	*	**	**	-
N-Cub.	*	ns	ns	ns	ns	-
Seed-Lin.	**	**	**	n/a	**	-
Seed-Quad	ns	ns	**	n/a	*	-
Seed-Cub.	ns	ns	ns	n/a	ns	-

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

In 2007 at Scott, there was an interaction between the effects of N and seed input levels for whole plant N uptake (Table 14). Nitrogen uptake increased linearly with increasing amounts of N fertilizer at all seeding rates and linearly and quadratically at the 50 seeds m^{-2} seed level. At the two lowest levels of N fertilizer, there was no effect of seeding rate on whole plant N uptake, however when the amount of N applied was 50 kg N ha^{-1} or higher, N uptake increased linearly with increasing seed inputs.

Table 17. Mean total N uptake at early flowering and orthogonal contrasts for canola grown at varying N fertilizer and seeding rates and N fertilizer rates at Scott 2007.

	SCOTT 2007						
Nitrogen Rate	Seeding Rates viable seeds m^{-2}				Orthogonal Contrasts		
kg N ha^{-1}	25	50	100	200	lin.	quad.	cub.
			kg N ha^{-1}				
0	36.7	40.9	40.2	40.4	ns	ns	ns
25	45.2	55.5	68.6	58.6	ns	ns	ns
50	50.8	58.3	67.3	83.2	**	ns	ns
100	60.2	89.9	95.5	102.1	**	ns	ns
150	63.7	89.8	105.8	106.6	**	*	ns
200	88.9	68.6	117.5	130.3	**	ns	**
Orthogonal Contrasts							
lin.	**	**	**	**			
quad.	ns	**	ns	ns			
cub.	ns	ns	ns	ns			

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

4.2.3 Grain Yield, Grain Nitrogen Concentrations, and Grain Nitrogen Removal

The overall F-tests for the effects of N fertilizer level on canola yield were always significant and the effects of seed level were significant in all cases except for Scott in 2007 where seed input level had no effect on grain yield (Table 16). A significant interaction between N and seed level was not observed for grain yield at any site-years. Overall yields were highest at Indian Head in 2005, with an overall mean of 2580 kg ha^{-1} and lowest at Scott in 2006 where the overall mean yield was 1080 kg ha^{-1}.

Canola grain yield increased linearly and quadratically with increasing amounts of N at all site-years except for Scott where yield increased linearly. Recall that the plots at Scott were severely damaged by hail at the flowering stage (HB4.2); however late-season conditions were warm and wet, allowing the canola to recover well. We speculate that the added vegetative growth required for the canola to recover from the hail may have increased the crop's N demands. If this were the case, the high N plots would have been able to recover from the damage more fully than the low N treatments. McGregor (1987) showed that when canola plots were hand thinned from 86 plants m^{-2} to 4 plants m^{-2} at the early vegetative stages, dry mattered accumulation continued well past flowering and the plants reached maturity 9-14 days later than those that were not thinned. Although the linear response of yield to N rate was significant at all site-years, the observed yield at the 200 kg ha^{-1} N level was never significantly different from the yield at the 150 kg ha^{-1} N level, and was only significantly higher than the 100 kg N ha^{-1} level 33% of the time. Other studies completed in western Canada have also reported reaching maximum canola yields with 100-150 kg ha^{-1} of N fertilizer (Karamanos et al. 2005; Malhi et al. 2007).

Table 18. 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}) at Indian Head and Scott (2005-07).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level			kg N ha^{-1}			
0 kg N ha^{-1}	1839c	1430e	1136d	1362d	889c	1193c
25 kg N ha^{-1}	2385b	1654.7d	1544c	1582c	957c	1375b
50 kg N ha^{-1}	2530b	2013c	1723bc	1680c	1009bc	1443b
100 kg N ha^{-1}	2838a	2420b	2062ab	2024b	1243a	1678a
150 kg N ha^{-1}	2937a	2578ab	2129a	2173ab	1164ab	1661a
200 kg N ha^{-1}	2951a	2629a	2302a	2361a	1215a	1621a
Seed Level						
25 seeds m^{-2}	2269b	1950c	1310c	n/a	1001b	1420
50 seeds m^{-2}	2782a	2083b	1760b	n/a	1036b	1539
100 seeds m^{-2}	2576a	2271a	1987ab	n/a	1082ab	1498
200 seeds m^{-2}	2692a	2180ab	2207a	n/a	1199a	1524
			ANOVA			
Source			p-values			
N-Level	**	**	**	**	**	**
Seed-Level	**	**	**	n/a	**	ns
N*Seed	ns	ns	ns	n/a	ns	ns
Replicate	ns	ns	ns	ns	ns	ns
Res. C.V.	12.4	8.7	22.2	13.5	17.0	12.6
Contrast						
N-Lin.	**	**	**	**	**	**
N-Quad.	**	**	**	ns	*	**
N-Cub.	ns	ns	ns	ns	ns	ns
Seed-Lin.	**	**	**	n/a	**	ns
Seed-Quad	*	**	**	n/a	ns	ns
Seed-Cub.	**	ns	ns	n/a	ns	ns

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

Grain yield increased linearly and quadratically with seed input level at all three years at Indian Head, whereby increasing the number of seeds planted beyond 100 seeds m^{-2} did not significantly increase grain yield (Table 16). The cubic orthogonal contrast was also significant in 2005 at Indian Head whereby the yield observed for the 100 seeds m^{-2} level was slightly lower than that observed at both the 50 and 200 seeds m^{-2} levels. There was a slight linear increase in yield with increasing levels of seed inputs at Scott in 2006; however the only significant difference was between the 25 and 200 seeds m^{-2} treatments and the difference was less than 200 kg ha^{-1}. There was no grain yield response to seed input levels at Scott in 2007. The lack of a response to seed input levels at Scott in 2007 was attributed to low seedling mortality with approximately 100% of the seeds planted becoming established at all but the highest seeding rate. The results of previous research looking at different seeding rates in canola are mixed. With low mortality, Morrison et al. (1989) found the optimum amount of seed was between 1.5 and 3 kg ha^{-1}, while Brandt et al. (2007) found that at least 5.8 kg ha^{-1} of seed were often required to maximize yields, especially at high N rates.

The overall F-test for the effects of N fertilizer level were always significant ofr grain N concentrations (g N kg grain^{-1}) while the F-test for the effects of seed input level were only significant at Indian Head in 2005 and Scott in 2006 (Table 17). There were no interactions observed between seed and N fertilizer levels with respect to grain N concentrations. Overall, seed protein concentrations were similar at Indian Head in 2006 and 2006 and slightly higher at Indian Head in and Scott in 2006 and 2007. Grain N concentrations at Scott in 2005 are not directly comparable with the other site-years because a different measurement technique was used at this site-year.

Table 19. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on canola grain N concentrations (g N kg grain^{-1}) at Indian Head and Scott (2005-07).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level			g N kg grain^{-1}			
0 kg N ha^{-1}	27.6c	28.4c	33.1b	39.6c	31.5c	30.0d
25 kg N ha^{-1}	28.9c	29.3c	33.2b	39.3c	30.9c	32.3c
50 kg N ha^{-1}	27.5c	30.1c	33.1b	39.3c	31.8c	33.1c
100 kg N ha^{-1}	31.5b	32.2b	35.8ab	40.5b	33.7b	36.1b
150 kg N ha^{-1}	32.9b	34.4a	37.6a	41.3a	36.3a	38.1a
200 kg N ha^{-1}	35.6a	35.8a	38.6a	41.8a	37.1a	39.5a
Seed Level						
25 seeds m^{-2}	31.1ab	31.7	35.6	n/a	34.5a	35.4
50 seeds m^{-2}	31.7a	32.1	34.6	n/a	33.7ab	35.1
100 seeds m^{-2}	29.4b	31.3	35.3	n/a	32.8b	34.5
200 seeds m^{-2}	30.3ab	31.7	35.4	n/a	33.2ab	34.3
			ANOVA			
Source			p-values			
N-Level	**	**	**	**	**	**
Seed-Level	*	ns	ns	n/a	*	ns
N*Seed	ns	ns	ns	n/a	ns	ns
Replicate	**	**	ns	ns	**	**
Res. C.V.	8.3	6.4	9.0	2.0	6.3	5.0
Contrast						
N-Lin.	**	**	**	**	**	**
N-Quad.	ns	ns	ns	ns	ns	**
N-Cub.	ns	ns	ns	**	*	ns
Seed-Lin.	ns	ns	ns	n/a	ns	*
Seed-Quad	ns	ns	ns	n/a	*	ns
Seed-Cub.	ns	ns	ns	n/a	ns	ns

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

Increasing the amount of N fertilizer applied always caused grain protein concentrations to increase linearly, and a cubic response was also detected in 2005 and 2006 at Scott. On average at Indian Head, grain N concentrations increased from 30 g kg^{-1} when no N was applied to 37 g kg^{-1} with the addition of 200 kg N ha^{-1}. The cubic response observed at Scott in 2005 and 2006 resulted from a slight depression in N concentrations at the 25 kg N ha^{-1} level, which was subsequently followed by increases in grain N with increasing amounts of N fertilizer. However, the cubic response to N input levels was not observed at Indian Head or at Scott in 2007 and, according the multivariate analysis, protein concentrations at the 25 kg ha^{-1} N rate were never significantly lower than those of the unfertilized check. Malhi and Gill (2007) also observed small reductions in grain protein with the addition of 50 kg N ha^{-1} when S fertilizer was applied. Other studies completed in western Canada have reported increased seed protein concentrations with increasing application rates of N fertilizer (Malhi and Gill 2004; Brandt et al. 2007).

According to the overall F-test, seed input level significantly affected canola grain N concentrations at Indian Head in 2005 and Scott in 2006 but not at the other site-years. At Indian Head, none of the orthogonal contrasts were significant for seed level and grain N concentrations; however, grain N at the 50 seeds m^{-2} rate was 2.3% higher than at the 100 seeds m^{-2} rate. At Scott in 2006, there was a quadric response whereby grain N decreased when the seeding rate was increased from 25 to 50 seeds m^{-2}, but further increasing the number of seeds planted beyond this level did not affect grain N concentrations. At Scott in 2007, grain N concentrations decreased linearly with increasing levels of seed inputs. Brandt et al. (2007) also found that grain protein concentrations of canola seeded at 2.8 kg ha^{-1} were slightly higher than for canola seeded at 5.6 or 8.4 kg ha^{-1}. In contrast, Morrison et al. (1990) did not observe any differences in canola seed protein content for seeding rates ranging from 1.5-12 kg ha^{-1}.

At all of the site-years except Scott in 2007, where seed input level did not affect grain N yields (seed level excluded from model at Scott in 2005), the quantity of N harvested in the canola seed (kg N ha^{-1}) was affected by both N fertilizer and seed input levels (Table 18). No significant interactions between the two variables were observed for grain N yields. Overall, the lowest mean quantities of N were harvested at Scott in 2006 (37 kg N ha^{-1}), while the most N was removed in the seed at Indian Head in 2005 (80 kg N ha^{-1}). Averaged across all treatments, the quantity of N removed in the seed was always lower than the average applied N rate of 87.5 kg ha^{-1}.

At all site-years, grain N yields always increased with increasing application rates of fertilizer N. The response was linear at all site years and the quadratic orthogonal contrast was also significant at Indian Head in 2005 and 2006. In all cases except for Scott in 2006 and 2007, grain N yields at the 50 kg N ha^{-1} fertilizer level exceeded the quantity of N applied; however this was never the case at the 100 kg N ha^{-1} fertilizer rate. When S fertility was not limiting, Malhi and Gill (2007) found that 150 kg N ha^{-1} or more was required to maximize the quantity of N harvested in canola seed even though, as a result of lower grain yields, the observed levels of N removed in their study were generally lower than those observed in the current study.

Except for Scott in 2007 where there was no response, the quantity of N removed in the grain was affected by seed input level at all of the site-years, whereby N yields tended to increase as the seeding rate was increased. Overall, the patterns observed were similar to those observed for grain yield, except perhaps with slightly smaller ranges because of the tendency for grain N concentrations to be slightly higher at the lower seed input levels. Grain N yields increased linearly and quadratically with increasing seed input levels at Indian Head in 2005 and 2006. The cubic orthogonal contrast for the effects of seed input level of grain N yield was significant at Indian Head in 2005 and so was the quadratic contrast at Scott in 2006.

Table 20. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N and seeding rates on grain N yields at Indian Head and Scott (2005-07).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level			kg N ha^{-1}			
0 kg N ha^{-1}	51.3d	41.2e	37.6c	53.9d	28.4b	36.1c
25 kg N ha^{-1}	69.7c	48.5d	53.3cb	62.3cd	29.6b	44.5b
50 kg N ha^{-1}	70.0c	60.5c	58.0b	66.0c	32.0b	47.6b
100 kg N ha^{-1}	89.8b	77.8b	74.3a	81.8b	42.0a	60.6a
150 kg N ha^{-1}	96.4ab	88.7a	80.0a	89.7b	42.3a	62.8a
200 kg N ha^{-1}	105.3a	94.0a	89.2a	98.7a	45.0a	63.9a
Seed Level						
25 seeds m^{-2}	71.6c	63.1b	47.1c	n/a	35.0b	50.6
50 seeds m^{-2}	89.4a	67.8ab	62.1b	n/a	35.3b	54.5
100 seeds m^{-2}	77.3bc	72.5a	72.0ab	n/a	35.8ab	52.4
200 seeds m^{-2}	83.3ab	70.5a	80.3a	n/a	40.2a	57.8
			ANOVA			
Source			p-values			
N-Level	**	**	**	**	**	**
Seed-Level	**	**	**	n/a	*	ns
N*Seed	ns	ns	ns	n/a	ns	ns
Replicate	ns	ns	ns	ns	**	**
Res. C.V.	18.4	10.4	27.9	13.7	19.1	12.4
Contrast						
N-Lin.	**	**	**	**	**	**
N-Quad.	*	**	ns	ns	ns	**
N-Cub.	ns	ns	ns	ns	ns	ns
Seed-Lin.	ns	**	**	n/a	ns	ns
Seed-Quad	ns	**	*	n/a	**	ns
Seed-Cub.	**	ns	ns	n/a	ns	ns

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

4.2.4 Nitrogen Use Efficiency and Fall Residual Soil Nitrate Concentrations

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). Agronomic NUE was highly variable from one site year to the next, ranging from 11.8 kg kg^{-1} on average at Indian Head in 2005 to as low as 2.4 at Scott in 2006 (Table 19). The levels of variability for ANUE were also high within each site-year with CV values ranging from 62-227%; therefore it was difficult to detect significant differences between the treatments. The overall F-test was significant for N rate at Indian Head in 2005 and Scott in 2007 only, while the F-test for seeding rate was significant at Indian Head in 2006 and 2007 and Scott in 2007. No interactions between the effects of the two variables on ANUE were observed.

Table 21. 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 (ANUE) at Indian Head and Scott (2005-07).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level			kg kg^{-1}			
25 kg N ha^{-1}	22.0a	9.0	16.3	8.8a	2.7	7.3a
50 kg N ha^{-1}	13.9ab	11.7	11.7	6.4a	2.4	5.0ab
100 kg N ha^{-1}	10.0b	9.9	9.3	6.6a	3.5	4.8ab
150 kg N ha^{-1}	7.3b	7.7	6.6	5.4a	1.8	3.1ab
200 kg N ha^{-1}	5.6b	6.0	5.8	5.0a	1.6	2.1b
Seed Level						
25 seeds m^{-2}	10.6	10.7ab	1.1b	n/a	3.3	3.4b
50 seeds m^{-2}	12.5	7.1bc	10.1ab	n/a	1.0	7.3a
100 seeds m^{-2}	11.6	12.2a	9.4ab	n/a	2.4	4.5ab
200 seeds m^{-2}	12.4	5.5c	19.2a	n/a	3.0	2.7b
			ANOVA			
Source			p-values			
N-Level	**	ns	ns	ns	ns	*
Seed-Level	ns	**	**	n/a	ns	*
N*Seed	ns	ns	ns	n/a	ns	ns
Replicate	ns	*	ns	ns	*	**
Res. C.V.	104.6	61.6	133.1	123.8	227.4	107.9
Contrast						
N-Lin.	**	*	*	ns	ns	**
N-Quad.	ns	ns	ns	ns	ns	ns
N-Cub.	ns	ns	ns	ns	ns	ns
Seed-Lin.	ns	*	**	n/a	ns	ns
Seed-Quad	ns	ns	ns	n/a	ns	ns
Seed-Cub.	ns	**	ns	n/a	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 $p < 0.01$

For N fertilizer level, the general tendency was for ANUE to be highest at low to moderate N rates and lowest at the 200 kg N ha^{-1} fertilizer level. Nitrogen use-efficiency decreased linearly with increasing quantities of N in all three years at Indian Head and in 2007 at Scott. Although the variability was high at the remaining site-years, the overall trends were similar for all of the site-years. The soils at Indian Head were more responsive to N fertilizer than at Scott. At Indian Head, ANUE at the 200 kg N ha^{-1} rate ranged from 5.7-16.4 kg kg^{-1} lower than for the N rate with the highest efficiency (25-50 kg N ha^{-1}) while at Scott the differences ranged from 1.9-5.2 kg kg^{-1}. 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} when 10 kg N ha^{-1} was applied 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 grown 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 as the quantity of N applied was increased.

With respect to the effects of seed input levels on ANUE, the observed patterns did not necessarily follow the same patterns as for grain yield, as ANUE was dependant on the yield of the unfertilized check within each level of seed inputs. At Indian Head in both 2006 and 2007, where the main effects of seed input level on ANUE were significant, the opposite effects were observed, whereby ANUE in 2006 decreased slightly with increasing seeding rates and in 2007 the response was positive. Nitrogen use efficiency at the 25 seeds m^{-2} level at Indian Head in 2007 was only 1.1 kg kg^{-1}, indicating a very weak response to N at low plant populations at this site year. Brandt et al. (2007) found that high plant populations were often required for canola to respond to large quantities of N, and vice versa. At Scott in 2007, the ANUE response to seed input level was cubic, with the greatest efficiency observed at the 50 seeds m^{-2} rate.

Residual soil NO_3-N was measured after harvest in all three years at Indian Head and in 2006 and 2007 at Scott. Seed input level was not included in the model for the analyses of soil NO_3-N because we only sampled the 100 seeds m^{-2} plots at Indian Head in 2006 and 2007 and preliminary analyses indicated that seed input level had no effect on residual soil NO_3-N. For the 0-60 cm soil depth, the overall F-tests for the effect of N rate were significant at Indian Head in 2005 and Scott in 2006, but not in any other cases (Table 20). At both of these site-years, residual soil NO_3-N levels at the 200 kg ha^{-1} rate were significantly higher than those observed for any other treatment. A similar trend was observed at all of the site-years, with soil NO_3-N concentrations always increasing linearly with increasing quantities of fertilizer N. At Indian Head in 2005 and Scott in 2006, the quadratic contrast for the effect of N rate on soil NO_3-N concentrations was also significant, whereby NO_3-N only began to accumulate in the soil when N rates exceeded 150 kg N ha^{-1}.

At Indian Head in 2005 and 2006, we sampled the soil to a depth of 120 cm to determine if NO_3-N was potentially being leached below the rooting zone at the higher N rates. In 2005, N rate had no effect on residual NO_3-N levels for the 60-120 cm soil depth (Table 21). In contrast, at Indian Head in 2007, residual soil NO_3-N increased with increasing N rates for the 60-120 cm profile. Although only the linear contrast was significant, the greatest increase in soil NO_3-N concentrations were observed when the N rate was increased from 150-200 kg N ha^{-1}; however the overall variability was high (C.V. = 128%). Overall, our results are in agreement with Smith et al. (1988) where although increasing the quantity of N applied from 20-100 kg N ha^{-1} had little effect on soil NO_3-N levels in the 0-50 cm soil profile, further increases to 200 kg N ha^{-1} increased residual NO_3-N levels.

Table 22. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N fertilizer rates on the soil residual NO_3-N concentrations of the 0-60 cm soil depth at Indian Head and Scott (2005-07).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level	kg NO_3-N ha^{-1} (0 – 60 cm)					
0 kg N ha^{-1}	26.0c	9.4	33.0	na	15.8b	13.9c
25 kg N ha^{-1}	31.4bc	10.7	33.4	na	15.1b	15.1c
50 kg N ha^{-1}	25.5c	22.8	23.3	na	14.9b	13.3c
100 kg N ha^{-1}	33.0bc	13.1	38.2	na	15.4b	18.2bc
150 kg N ha^{-1}	39.8b	18.1	40.5	na	19.5b	35.1b
200 kg N ha^{-1}	58.3a	54.9	81.5	na	44.8a	61.5a
	ANOVA					
Source	p-values					
N-Level	**	ns	ns	na	**	**
Replicate	ns	ns	ns	na	**	ns
Res. C.V.	34.8	94.0	70.0	na	93.4	79.0
Contrast						
N-Lin.	**	**	*	na	**	**
N-Quad.	**	ns	ns	na	**	**
N-Cub.	ns	ns	ns	na	ns	ns

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

Table 23. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N fertilizer rates on the soil residual NO_3-N concentrations of the 60-120 cm soil depth at Indian Head and Scott (2005-07).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level	kg NO_3-N ha^{-1} (60 - 120 cm)					
0 kg N ha^{-1}	na	6.2	6.9	na	na	na
25 kg N ha^{-1}	na	6.2	24.2	na	na	na
50 kg N ha^{-1}	na	16.1	5.5	na	na	na
100 kg N ha^{-1}	na	6.8	23.7	na	na	na
150 kg N ha^{-1}	na	20.3	15.7	na	na	na
200 kg N ha^{-1}	na	17.1	57.5	na	na	na
	ANOVA					
Source	p-values					
N-Level	na	ns	ns	na	na	na
Replicate	na	ns	ns	na	na	na
Res. C.V.	na	81.0	128.0	na	na	na
Contrast						
N-Lin.	na	ns	*	na	na	na
N-Quad.	na	ns	ns	na	na	na
N-Cub.	na	ns	ns	na	na	na

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

When the two soil depths for which soil analyses were completed at Indian Head in 2006 and 2007 were combined, the overall F-test was not significant in either year (Table 22). However, in both cases, fall residual soil NO_3-N concentrations increased linearly with increasing N rates. Although the quadratic response at Indian Head in 2007 was not significant, again likely a result of high variability, 139 kg NO_3-N ha^{-1} was measured in the 150 kg N ha^{-1} treatment for the 0-120 cm soil profile, which was more than two times that observed at the 150 kg N ha^{-1} fertilizer rate.

Table 24. Treatment means and tests of significance for ANOVA test and orthogonal contrasts for the effects of N fertilizer rates on the soil residual NO_3-N concentrations of the 0-120 cm soil depth at Indian Head and Scott (2005-07).

	Indian Head			Scott		
	2005	2006	2007	2005	2006	2007
N Level	kg NO_3-N ha^{-1} (0 – 120 cm)					
0 kg N ha^{-1}	na	15.6	40.0	na	na	na
25 kg N ha^{-1}	na	16.9	57.6	na	na	na
50 kg N ha^{-1}	na	38.9	28.9	na	na	na
100 kg N ha^{-1}	na	19.9	61.9	na	na	na
150 kg N ha^{-1}	na	38.4	56.1	na	na	na
200 kg N ha^{-1}	na	72.0	139.0	na	na	na
Source	**ANOVA** p-values					
N-Level	na	ns	ns	na	na	na
Replicate	na	ns	ns	na	na	na
Res. C.V.	na	82.3	78.6	na	na	na
Contrast						
N-Lin.	na	*	*	na	na	na
N-Quad.	na	ns	ns	na	na	na
N-Cub.	na	ns	ns	na	na	na

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

4.2.5 NDVI – Yield Relationship for Individual Site-Year / Sensing Dates

The first step towards establishing whether it is possible to estimate canola yield using NDVI measurements was to examine the exponential NDI-yield relationships for each site-year/sensing date. Doing so enabled us to determine the range of growth stages where these two variables were correlated, which would then be the recommended range for using the final yield potential equations. Parameter estimates, coefficients of determination, and p-values for each sensing date are presented separately for each location in Tables 23-27.

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 23). However from June 14 onward, the relationship improved as the crop developed, peaking at R^2=0.629 just before the canola went into full flower (HB4.1-4.2). Similar trends were observed in 2006 whereby the NDVI-yield relationship improved 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. Due to technical problems in 2007 at Brandon, NDVI data is only available for growth stages HB2.3-2.6. During these stages, the relationship between NDVI and canola yield was weak, although still statistically significant.

Table 25. Parameter estimates and 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[z] $y = a*\exp(b*x)$			
Year	Date	Crop Stage	***a***	***b***	**Adj. R^2**	**P-Value**
2005	June 3	1 – 2.1	1586 (366)	0.76 (1.24)	0.000	0.363
	June 7	2.2	1822 (239)	0.00 (0.49)	0.000	DNC[x]
	June 14	2.3	1151 (143)	1.48 (0.38)	0.133	**<0.001**
	June 21	2.4	1086 (92)	1.19 (0.17)	0.339	**<0.001**
	June 28	3.2	809 (76)	1.25 (0.13)	0.523	**<0.001**
	June30	3.3	732 (68)	1.45 (0.13)	0.590	**<0.001**
	July5	4.1 – 4.2	478 (60)	2.00 (0.18)	0.629	**<0.001**
	July 13	5.1	688 (147)	1.60 (0.34)	0.185	**<0.001**
2006	June 13	2.1 – 2.2	570.2 (72)	3.00 (0.52)	0.250	**<0.001**
	June 16	2.3	599 (51)	2.66 (0.32)	0.406	**<0.001**
	June 19	2.4	698 (50)	1.65 (0.20)	0.410	**<0.001**
	June 23	3.2	678 (40)	1.17 (0.12)	0.525	**<0.001**
	June 26	3.3	657 (41)	1.11 (0.11)	0.529	**<0.001**
	July 6	4.2	239 (44)	2.39 (0.27)	0.499	**<0.001**
	July 10	4.3	256 (68)	2.38 (0.42)	0.289	**<0.001**
2007[y]	June 15	2.3	763 (113)	1.15 (0.37)	0.084	**0.002**
	June 20	2.6	742 (80)	0.93 (0.20)	0.181	**<0.001**

[z]Data analyzed using SigmaPlot 10 (Systat Software Inc.)
[y]No NDVI data is available past June 20 due to technical problems at Brandon in 2007
[x]DNC – model did not converge

The strength of the NDVI-yield relationship over the course of the growing season at Indian Head followed similar patterns as for Brandon (Table 24). In 2005 and 2006, the NDVI-yield correlation was initially very weak and improved as the growing season progressed. In both 2005 and 2006 at Indian Head, the correlation peaked when the crop was between growth stages HB3.3-4.1. 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 and the dropping of leaves after flowering interfere with the ability of NDVI to detect variability in canola canopies late in the season (Basnyat et al. 2004). In 2006, however, the relationship between NDVI and grain yield was very strong (R^2=0.820) when the crop was at growth stage HB5.1. While this indicates that late-season NDVI measurements can potentially be well-suited for estimating canola yield potential, N deficiencies of canola cannot be corrected this late in the season (Holzapfel et al. 2007; Lafond et al. 2008). In 2007 at Indian Head, NDVI measurements are only available for growth stages HB3.3-4.1 and the NDVI-yield relationship was reasonably strong for each of the three sensing dates (R^2=0.547-0.549)

Table 26. Parameter estimates and adjustedz 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**	**P-Value**
2005	June 5	1 – 2.1	2336 (138)	1.10 (0.60)	0.024	0.072
	June 11	2.2 – 2.3	2145 (116)	1.40 (0.37)	0.120	**<0.001**
	June 19	2.4 – 2.6	1891 (90)	0.72 (0.10)	0.373	**<0.001**
	June 23	3.1 – 3.2	1604 (85)	0.86 (0.09)	0.530	**<0.001**
	June 28	3.3 – 4.1	1062 (70)	1.22 (0.09)	0.730	**<0.001**
	July 7	4.3 – 4.4	1607 (220)	0.91 (0.26)	0.113	**<0.001**
2006	June 1	1 – 2.1	1026 (414)	5.56 (3.14)	0.021	0.086
	June 8	2.2 – 2.3	1543 (190)	2.18 (0.82)	0.060	**0.009**
	June 13	2.3 – 2.4	1662 (165)	0.99 (0.38)	0.056	**0.012**
	June 16	2.4 – 2.5	1545 (140)	0.84 (0.23)	0.119	**<0.001**
	June 22	2.6 – 3.1	1161 (122)	1.01 (0.17)	0.283	**<0.001**
	June 25	3.1 – 3.2	930 (106)	1.29 (0.17)	0.392	**<0.001**
	June 28	3.3 – 4.1	638 (79)	1.68 (0.17)	0.554	**<0.001**
	August 2	5.3	175 (24)	3.77 (0.20)	0.820	**<0.001**
2007	June 25	3.3 – 4.1	690 (75)	1.67 (0.17)	0.547	**<0.001**
	June 26	3.3 – 4.1	637 (72)	1.83 (0.18)	0.565	**<0.001**
	June 27	4.1	553 (69)	1.96 (0.19)	0.591	**<0.001**

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 correlation between grain yield and NDVI was weak at Ottawa in 2005 (Table 25); however, the overall trend was the same whereby the relationship improved as the crop progressed through vegetative stages, peaked just prior to flowering (R^2=0.196) and became relatively weak at full bloom (R^2=0.096). In contrast to the results from Indian Head in 2007, the NDVI-yield relationship was very weak during pod-filling at Ottawa. In 2006 at Ottawa, the NDVI-yield relationship was strong throughout the vegetative growth stages and reached peak strength during the early bolting stage (HB3.1-3.2). Compared with 2006, the NDVI-yield relationship prior to bolting (HB3.1) was slightly weaker in 2007. The coefficient of correlation was highest at growth stage HB3.3 (0.589)

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Table 27. 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).

Year	Date	Crop Stage	Parameter estimates $y = a*\exp(b*x)$ ***a***	***b***	**Adj. R^2**	**P-Value**
	June 1	2.1	2762 (185)	0.79 (0.22)	0.111	**<0.001**
	June 3	2.1 – 2.2	2746 (181)	0.52 (0.13)	0.127	**<0.001**
	June 7	2.4 – 2.5	2648 (178)	0.51 (0.12)	0.161	**<0.001**
2005	June 10	2.5 – 2.7	2236 (215)	0.67 (0.14)	0.196	**<0.001**
	June 20	4.2	296 (191)	3.15 (0.84)	0.132	**<0.001**
	June 23	4.3	665 (321)	2.17 (0.66)	0.096	**<0.001**
	June 29	5.2	723 (360)	2.19 (0.68)	0.095	**0.001**
	May 29	2.2	686 (100)	8.86 (1.06)	0.476	**<0.001**
	June 2	2.3	1406 (79)	2.11 (0.23)	0.529	**<0.001**
	June 5	2.4	1544 (73)	1.29 (0.15)	0.507	**<0.001**
	June 9	2.5	1116 (82)	1.14 (11)	0.603	**<0.001**
	June 12	2.6	1195 (84)	1.00 (0.10)	0.580	**<0.001**
2006	June 16	2.7	963 (78)	1.32 (0.12)	0.643	**<0.001**
	June 19	3.1 – 3.2	441 (85)	2.19 (0.25)	0.539	**<0.001**
	June 23	3.3 – 4.1	290 (81)	2.67 (0.35)	0.476	**<0.001**
	June 30	4.2 – 4.3	2254 (645)	0.00 (0.41)	0.000	DNC[x]
	July 6	4.4 – 5.1	710 (199)	1.92 (0.45)	0.187	**<0.001**
	July 21	5.2 – 5.3	730 (362)	1.53 (0.67)	0.058	**0.023**
	May 28	1 – 2.1	956 (224)	2.39 (1.39)	0.026	0.092
	June 1	2.2	1092 (149)	0.69 (0.34)	0.041	**0.048**
	June 8	2.5	1027 (103)	0.69 (0.19)	0.135	**<0.001**
	June 11	2.6	852 (104)	0.91 (0.20)	0.212	**<0.001**
	June 15	2.7 – 3.0	526 (103)	1.57 (0.30)	0.282	**<0.001**
2007	June 18	3.1 – 3.2	136 (0.36)	3.44 (0.37)	0.571	**<0.001**
	June 21	3.3	36.0 (15)	4.84 (0.53)	0.589	**<0.001**
	June 24	4.1	175 (56)	2.90 (0.43)	0.412	**<0.001**
	June 28	4.3	296 (82)	2.62 (0.45)	0.318	**<0.001**
	July 3	5.1	192 (49)	3.58 (0.45)	0.483	**<0.001**

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
[x]DNC – model did not converge

In all three years at Scott, there was no correlation between NDVI and grain yield until the crop reached growth stages HB2.4-2.5 (Table 26). Despite the hail damage, the strongest correlation between NDVI and yield at Scott occurred at growth stage HB3.1 in 2005. Similar to the other locations, the correlations at Scott was best between growth stages HB3.1-HB4.2 and became comparatively weak during full bloom (HB4.1-4.2).

The overall NDVI-yield relationship at Scott was weak in 2006 relative to 2005, likely a result of hot, dry conditions during flowering reducing the overall grain yield potential (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 can not always be expected because environmental factors such as drought, frost, hail, or disease, can reduce yield potential after the NDVI data has been acquired. In 2007 at Scott, while the NDVI-yield relationship was reasonably strong (R^2=0.404) at growth stages HB4.1-4.2, the coefficient of correlation for the remaining measurements were comparatively low (R^2<0.30). Again, it is possible that the relatively low correlation coefficients observed at Scott in 2007 were at least partly due to hot dry conditions during flowering and pod filling.

Table 28. 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**	**P-value**
2005	June 8	2.1 – 2.2	1864 (281)	0.00 (0.39)	0.000	DNC[x]
	June 16	2.3	1523 (247)	0.34 (0.27)	0.006	0.214
	June 21	2.4	647 (123)	1.39 (0.25)	0.269	**<0.001**
	June 24	2.5 – 2.6	384 (83)	1.99 (0.26)	0.426	**<0.001**
	June 27	3.1	134 (44)	3.13 (0.38)	0.465	**<0.001**
	June 30	3.3	123 (43)	3.32 (0.41)	0.456	**<0.001**
2006	June 7	2.2	929 (167)	0.81 (0.97)	0.000	0.398
	June 14	2.4	841 (82)	0.94 (0.35)	0.060	**0.009**
	June 16	2.4 – 2.5	814 (63)	0.79 (0.20)	0.126	**<0.001**
	June 19	2.5	827 (55)	0.67 (0.15)	0.157	**<0.001**
	June 22	2.5	802 (54)	0.59 (0.12)	0.189	**<0.001**
	June 26	2.6 – 3.2	684 (68)	0.71 (0.15)	0.195	**<0.001**
	June 30	3.3 – 4.1	390 (75)	1.41 (0.26)	0.247	**<0.001**
	July 4	4.3	771 (145)	0.50 (0.28)	0.025	0.065
	July 6	4.3 – 4.4	1079 (154)	0.00 (0.25)	0.000	DNC[x]
2007	June 5	2.2	1342 (176)	0.57 (0.68)	0.000	0.405
	June 12	2.4	1390 (86)	0.23 (0.19)	0.005	0.219
	June 15	2.4 – 2.5	1366 (74)	0.24 (0.14)	0.022	0.078
	June 19	2.6 – 3.1	1327 (71)	0.24 (0.10)	0.048	**0.019**
	June 22	3.1 – 3.2	1169 (79)	0.42 (0.11)	0.137	**<0.001**
	June 25	3.3 – 4.1	947 (85)	0.69 (0.13)	0.230	**<0.001**
	June 29	4.1 – 4.2	613 (72)	1.29 (0.17)	0.404	**<0.001**
	July 3	4.3	1017 (97)	0.70 (0.17)	0.151	**<0.001**
	July 6	5.1	1048 (104)	0.69 (0.19)	0.119	**<0.001**

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
[x]DNC – model did not converge

Table 29. 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**	**P-Value**
2005	June 10	2.1	1204 (321)	0.25 (1.50)	0.00	0.867
	June 14	2.2	1068 (172)	0.76 (0.70)	0.002	0.279
	June 16	2.2 – 2.3	1004 (126)	1.01 (0.50)	0.031	**0.048**
	June 20	2.4 – 2.5	957 (116)	1.04 0.40)	0.056	**0.012**
	June 22	2.5 – 3.1	836 (101)	1.26 (0.32)	0.133	**<0.001**
	June 27	3.2 – 4.1	562 (73)	1.75 (0.24)	0.372	**<0.001**
	July 4	4.1 – 4.2	218 (34)	3.09 (0.25)	0.707	**<0.001**
	July 6	4.2 – 4.3	486 (68)	1.79 (0.23)	0.460	**<0.001**
	July 12	4.3 – 4.4	540 (88)	1.94 (0.33)	0.308	**<0.001**
	July 18	5.1 – 5.2	638 (147)	1.43 (0.46)	0.097	**0.001**
2006	June 6	1 – 2.1	89 (40)	12.9 (3.3)	0.131	**<0.001**
	June 12	2.1 – 2.2	164 (46)	4.49 (1.10)	0.133	**<0.001**
	June 15	2.3 – 2.4	223 (30)	3.82 (0.56)	0.304	**<0.001**
	June 19	2.3 – 2.5	253 (24)	2.85 (0.33)	0.409	**<0.001**
	June 21	2.4 – 2.5	243 (23)	2.82 (0.30)	0.469	**<0.001**
	June 23	2.5 – 2.6	232 (22)	1.97 (0.20)	0.516	**<0.001**
	June 30	3.3 – 4.1	138 (16)	2.49 (0.20)	0.676	**<0.001**
	July 4	4.2 – 4.4	115 (22)	2.48 (0.30)	0.469	**<0.001**
2007	June 5	2.2 – 2.3	186 (41)	4.7 (1.39)	0.094	**0.001**
	June 8	2.2 – 2.4	239 (38)	2.65 (0.84)	0.085	**0.002**
	June 11	2.3 – 2.5	253 (31)	2.04 (0.55)	0.114	**<0.001**
	June 13	2.5 – 3.1	244 (29)	1.92 (0.45)	0.157	**<0.001**
	June 15	3.1	244 (28)	1.50 (0.34)	0.174	**<0.001**
	June 19	3.2	216 (25)	1.64 (0.30)	0.252	**<0.001**
	June 21	3.3	183 (21)	1.76 (0.25)	0.376	**<0.001**
	June 22	3.3 – 4.1	163 (19)	2.26 (0.27)	0.453	**<0.001**
	June 25	4.1	127 (19)	1.97 (0.24)	0.463	**<0.001**
	June 27	4.2	134 (20)	1.85 (0.24)	0.446	**<0.001**
	June 29	4.3	120 (16)	2.23 (0.24)	0.538	**<0.001**

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

At Swift Current in 2005, there no correlation between NDVI and grain yield prior to the early bolting stage (HB3.1; Table 27). The correlation coefficients then increased rapidly as the crop approached flowering, peaking at 0.707 at growth stage HB4.1-4.2), and proceeded to weaken as the crop went into and beyond full bloom. Although the NDVI-yield relationship in 2006 at Swift Current was slightly weaker than that in 2005, the temporal patterns were the same and the R^2 peaked at 0.676 (HB3.3 – 4.1). Similar patterns were observed in 2007 at Swift Current, except the NDVI-yield relationship remained comparatively strong through flowering. The response to N was weak at Swift Current in 2007, thus the range in grain yields was small and the NDVI-yield curves relatively flat compared to the other sites-years.

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 pattern reported for corn (Martin et al. 2007). The weak NDVI-yield relationship prior to HB2.5 was likely a result of there being insufficient levels of above-ground biomass relative to background soil levels to detect subtle differences in growth. Furthermore, the rate of N uptake peaks at the bud-formation / early bolting stage, reaching maximum total N uptake during the pod-filling stages (Malhi et al. 2007), thus it is unlikely that plants would show N deficiency symptoms prior to HB2.5. It is also possible that the variability in plant populations resulting from the different seed input levels have had a greater effect on early season NDVI measurements than for late-season NDVI and eventual grain yield. As canola plants develop, they compensate for low plant populations through increased branching and overall vegetative growth and a prolonged period of pod-filling (Rood and Major 1984; McGregor 1987; Morrison et al. 1990), especially when water and nutrients are in adequate supply (Angadi et al. 2003). The decline in NDVI and weakening NDVI-yield relationship observed late in the growing season was likely attributable to both to the scattering effect of the brightly coloured flowers along with overall plant senescence (Basnyat et al 2005; Martin et al. 2007). These results show that the ability of NDVI to estimate canola yield potential depends on the growth stage of the crop at sensing.

4.2.6 Normalizing NDVI to Improve Estimates of Canola Yield Potential

Based on the previous findings, we initially combined data from all of the site-years for dates where the canola was between growth stages HB2.5-4.1. The NDVI values were then divided by various normalizing values to account for differences in crop growth between years and locations (Raun et al. 2002; Teal et al. 2006). Data from all sites for 2005 and 2006 have been previously analyzed and summarized in Holzapfel (2007) and are presented again in Table 28. For this analysis, data from Scott in both 2005 and 2006 were excluded because the plots were damaged by hail in both years and from Swift Current in 2006 because late-season growing conditions were extremely hot and dry, presumably resulting in yield losses which the sensor measurements could not account for. With the exception of Ottawa, conditions were hot and dry in 2006 at all of the locations, but the drought appeared to have a greater impact on yields at Swift Current and, to a lesser extent, Scott, than it did at the other locations and Raun et al. (2005) recommend excluding data from fields where adverse post-sensing conditions reduce grain yields. With winter wheat, Raun et al. (2001) demonstrated how including such data can weaken the overall NDVI-yield relationship. Refer to Appendix A for graphical representations of the NDVI-yield relationships presented in Table 24, in addition to the initial analysis where data from Scott and Swift Current in 2006 are also included.

Table 30. Parameter estimates and adjusted[z] coefficients of determination describing the exponential relationship between NDVI divided by various normalizing values (x) and canola seed yield (y) for canola between crop stages 2.5 and 4.2 (Harper and Berkenkamp 1975) at all 2005-06 locations except Scott in 2005 and 2006 and Swift Current in 2006. Values enclosed in brackets are standard errors of the parameter estimates (n = 1799) and all regression analyses are significant at P<0.001 (adapted from Holzapfel 2007).

	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

For the following analyses, the NDVI-yield data used to generate the equations presented in Table 23 were used as a starting point to which all data from 2007 for growth stages HB2.5-4.2 were added. Adding data from the appropriate growth stages for all locations in 2007 weakened the NDVI-yield relationship considerably, with the correlation coefficient decreasing from 0.444 to 0.378 (Table 29). Aside from using DFP and P-days as normalizing values improving the NDVI-yield relationship slightly, dividing NDVI by the normalizing values did not typically improve the relationship and, in the case of corn heat units, substantially worsened the relationship (R^2=0.130). Similar to 2006, visual inspection of the data revealed that the 2007 yields from Swift Current, and to a lesser extent Scott, did not exhibit the same relationship with NDVI as the other sites (Figures A-13-A-19. At the higher NDVI values, the observed yields at these sites were considerably lower (Swift Current in particular) than the observed yields at the other site-years where similar NDVI were recorded. This was particularly evident when NDVI was divided by CHU (Figure A-18), which, interestingly, always resulted in the strongest correlation when data from Swift Current (2006-07) and Scott (2005-07) were excluded (Tables 28 and 30).

As in 2006, we attributed the relatively low grain yields observed at Swift Current and to a lesser extent Scott to the hot dry conditions that occurred late in the season (Angadi et al. 2000; Morrison and Stewart 2002). The fact that this occurred two years out of three may indicate the need to approach sensor-based N management differently in the Brown and Dark Brown Soil Zones compared to in the Black Zone. The NDVI-yield relationship at Swift Current in 2005 was similar to that of the rest of the sites; therefore data from this site-year was included in the analyses that follow. However, the results from 2006 and 2007 suggest that decisions regarding post-emergent N in the Brown and Dark Brown Soil Zones in particular should be based primarily on in-season soil-moisture availability and the likelihood of receiving precipitation in the short-term future, with NDVI measurements and N-rich reference crops playing a secondary role in determining post-emergent N rates. We removed the data from Swift Current and Scott in 2007 to determine if the NDVI-yield relationships could be further refined. Results from these final analyses are presented in Table 30.

Table 31. Parameter estimates and adjusted[z] coefficients of determination describing the exponential relationship between NDVI divided by various normalizing values (x) and canola seed yield (y) for canola between crop stages 2.5 and 4.2 (Harper and Berkenkamp 1975). Data included that presented in Table 23 plus all data collected between growth stages 2.5 and 4.2 in 2007. Values enclosed in brackets are standard errors of the parameter estimates (n = 3335) and all regression analyses are significant at P<0.001.

	Parameter estimates $y = a*\exp(b*x)$		
x-axis	a	b	Adj. R^2
NDVI[y]	552.2 (16.4)	1.81 (0.04)	0.378
NDVI/DFP	619.1 (15.4)	64.2 (1.4)	0.387
NDVI/GDD_0	604.3 (16.4)	943.6 (22.7)	0.363
NDVI/GDD_5	704.1 (18.8)	514.7 (14.4)	0.293
NDVI/CHU	883.3 (27.1)	579.0 (27.1)	0.130
NDVI/P-Days	594.6 (15.6)	435.3 (9.8)	0.387

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

Table 32. Parameter estimates and adjusted[z] coefficients of determination describing the exponential relationship between NDVI divided by various normalizing values (x) and canola seed yield (y) for canola between crop stages 2.5 and 4.2 (Harper and Berkenkamp 1975). Data included that presented in Table 23 plus all data collected between growth stages 2.5 and 4.2 in 2007 except Scott and Swift Current. Values enclosed in brackets are standard errors of the parameter estimates (n = 2471) and all regression analyses are significant at P<0.001.

	Parameter estimates $y = a*\exp(b*x)$		
x-axis	a	b	Adj. R^2
NDVI[y]	777.6 (22.0)	1.43 (0.04)	0.351
NDVI/DFP	863.7 (20.6)	49.47 (1.37)	0.359
NDVI/GDD_0	739.3 (18.1)	877.8 (20.7)	0.437
NDVI/GDD_5	734.2 (17.8)	581.2 (13.4)	0.445
NDVI/CHU	733.9 (17.7)	936.9 (21.5)	0.447
NDVI/P-Days	836.6 (20.8)	336.5 (9.3)	0.363

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

The NDVI-yield relationship prior to normalizing NDVI with any of the potential values became slightly weaker when data from Scott and Swift Current in 2007 was removed (R^2=0.351; Figure A-20); however, with the exception of DFP and P-days, the normalized relationships were all an improvement over those presented in Table 29. The relative rankings of the various potential normalizing values in these final analyses were identical to that reported in Holzapfel (2007; Table 23) whereby CHU > GDD_5 > GDD_0 > P-days > DFP. Furthermore, the equations proposed in Holzapfel (2007) were all very similar to those which incorporated the selected 2007 data, albeit the new equations are slightly more conservative in their estimates (Appendix B). Despite the relatively low R^2 values, that the relationships changed very little after adding the data from 2007 suggests that these equations are good indicators of canola yield potential that should be suitable for a wide-range of conditions.

4.3 STUDY #2: Feasibility of Sensor-Based N Management

Our second objective was to examine the feasibility of using optical sensors and high N reference crops to determine N topdressing requirements relative to banding the entire N requirements at the time of seeding. Of particular interest were the effects of N management on grain yield (kg ha^{-1}) and N fertilizer use (kg N ha^{-1}); however we also measured grain N concentrations (g N kg $grain^{-1}$), the total quantity of N harvested in the seed (kg N ha^{-1}), agronomic N-use efficiency (ANUE), and fall residual soil NO_3-N (kg N ha^{-1}).

4.3.1 Crop Establishment, NDVI and Variable Rate N Fertilizer Use

Although variable from one site-year to the next, crop establishment was considered adequate at all site-years, with the observed plant densities ranging from 60-130 plants m^{-2} (Table 31). The Canola Council of Canada recommends targeting 75-150 plants m^{-2} (Canola Council of Canada 2005) while Angadi et al. (2003) found that canola yields were largely unaffected by plant populations ranging from 20-80 plants m^{-2}. Because N management did not affect plant populations in any cases, NH_3 toxicity was not considered a potentially confounding factor.

Table 33. Plant densities (plants m^{-2}) of canola established under various N management strategies at Indian Head and Scott in the 2005, 2006 and 2007 growing seasons.

	Indian Head			Scott		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Nitrogen Management	plants m^{-2}					
Check	72	81	72	113	62	72
N Rich (NR)	72	75	93	130	64	84
Farmer Practice (FPN)	84	78	84	113	62	85
Reduced N (RRN)	77	81	68	na	na	na
Split / Fixed (SFN)	73	68[y]	70	128	76	77
Variable Rate 1 (VRN1)	na	68	87	na	60	82
Variable Rate 2 (VRN2)	83	68	87	111	66	78
	Analysis of Variance					
Source	p > F					
Treatment	ns	ns	ns	ns	ns	ns
Replicate	**	ns	ns	**	[w]	ns
Residual C.V. (%)	16.1	27.5	15.3	19.4	18.4	13.6
	Selected Contrasts					
	p-value					
Check vs Rest	ns	ns	ns	ns	ns	ns
NR vs RRN+SFN+VRN	ns	ns	ns	ns	ns	ns
FPN vs RRN+SFN+VRN	ns	ns	ns	ns	ns	ns

[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]SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment
[x]Contrasts include both VRN 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 NDVI of each plot was measured using a handheld GreenSeeker™ sensor one to four days prior to the date of the post-emergent UAN applications. The dates of the in-crop N applications ranged from June 24-30 (Table 3) and the growth stages of the canola were between HB3.1-4.1. 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, separate or combined (Table 32). Behrens et al. (2004) also observed higher NDVI values for fertilized rapeseed canopies than for unfertilized ones.

In 2005 and 2006 at both locations, the NDVI of the individual VRN treatments always tended 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 site-years except Scott in 2005 and Indian Head in 2007, where in both cases the FPN treatment was higher. Furthermore, the NDVI of the NR treatment was not significantly higher than for the combined split-N treatments (SFN, VRN, and RRN) for any of the site-years except for 2005 and 2006 at Indian Head. The NDVI of the FPN treatment was higher than that of the reduced N treatments 50% of the time, the exceptions being Scott in 2006 and both sites in 2007. At Scott in 2006 and both sites in 2007, the only significant difference in NDVI among the treatments was between the unfertilized check and all other treatments; however the NDVI of the NR treatment tended to be higher than that of the combined split N treatments at Scott in 2006 (p=0.065).

Table 34. NDVI of canola grown under different N management strategies at Indian Head and Scott in 2005, 2006, and 2007. Canola was between the early-bolting stage and the start of flowering (HB3.1-4.1) and NDVI was determined using handheld GreenSeeker™ sensors just prior to topdressing N fertilizer.

	Indian Head			Scott		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Nitrogen Management	NDVI					
Check	0.271b	0.502c	0.445b	0.463c	0.637b	0.722b
N Rich (NR)	0.406a	0.769a	0.734a	0.594ab	0.749a	0.834a
Farmer Practice (FPN)	0.400a	0.751ab	0.737a	0.637a	0.714a	0.831a
Reduced N (RRN)	0.356a	0.711b	0.703a	na	na	na
Split / Fixed (SFN)	0.351a	0.730ab [y]	0.713a	0.562b	0.703a	0.833a
Variable Rate 1 (VRN1)	na	0.714ab	0.735a	na	0.714a	0.829a
Variable Rate 2 (VRN2)	0.382a	0.714ab	0.739a	0.577b	0.713a	0.820a
	Analysis of Variance					
Source	p > F					
Treatment	**	**	**	**	**	**
Replicate	*	ns	**	**	[w]	*
Residual C.V. (%)	8.4	3.6	5.1	4.1	4.9	3.6
	Selected Contrasts p-value					
Check vs Rest	**	**	**	**	**	**
NR vs RRN+SFN+VRN[x]	*	**	ns	ns	ns	ns
FPN vs RN+SFN+VRN	*	*	ns	**	ns	ns

[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]SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment
[x]Contrasts include both VRN 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; *significant at $0.01 \leq p \leq 0.05$; **significant at $p < 0.01$

Depending on the site-year and yield potential equation used, the sensor-based estimates of yield potential for the NR treatments ranged from 2430-5122 kg ha^{-1}, (Table 33). The lowest yield potential estimated for the NR treatment was with the VRN1 equation at Indian Head in 2007 while the highest was with the VRN2 equation at Scott in 2007. Table 33 illustrates the comparatively optimistic yield potential estimates that are derived using VRN2 relative to VRN1. However, the yield potential estimates of the NR and VRN2 treatments are equally optimistic; thus the N recommendations tended to be similar to those recommended using VRN1. With all other factors being equal, the rates recommended using VRN2 are 33% higher than for the same plots with VRN1.

Table 35. Estimated yield potentials (kg ha^{-1}) and estimated post-emergent N requirements (kg N ha^{-1}) of canola in the VRN treatments as well as total N fertilizer savings in this treatment relative to the FPN treatment within the same site-year.

		Indian Head					Scott				
		2005	**2006**		**2007**		**2005**	**2006**		**2007**	
		na	VRN1	VRN2	VRN1	VRN2	na	VRN1	VRN2	VRN1	VRN2
		days									
Calendar Days[z]		44	45		48		36	43		44	
		˚C									
GDD[y]		539	612		597		439	588		523	
		kg ha^{-1}									
Estimated YP[x]	NR	2466	2691	3579	2430	3233	3877	2739	3642	3849	5122
	VRN	2387	2467	3283	2436	3218	3840	2587	3436	3700	4833
	NR-VRN	**79**	**224**	**296**	**(-6)**	**15**	**37**	**152**	**206**	**149**	**289**
N Required[w]	Mean	6	15	20	2	1	4	10	14	9	19.0
	Min	0	0	4	0	0	0	0	7	2	3
	Max	11	29	40	9	2	11	22	22	17	50
N savings[v] (FPN – VRN)	Mean	**53**	**43**	**39**	**32**	**33**	**56**	**24**	**20**	**25**	**15**
	Min	48	29	18	25	32	49	12	12	17	(-16)
	Max	59	58	54	34	34	57	34	27	32	31

[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
[w]Topdress N rate recommended for canola plots in the VRN treatment using optical sensors
[v]Total quantity of N fertilizer applied in the VRN treatment subtracted from the rate applied in FPN treatment
na – Only one VRN treatment was included in 2005, which is directly comparable to VRN2 in 2006

The greatest estimated potential response to topdressed N was at Indian Head in 2006 where a 9% increase in yield was predicted, while the smallest was at Indian Head in 2007, where the estimated yield potential of the VRN treatment was slightly higher than the NR treatment. It is unlikely that the relatively small yield responses to topdressed N predicted at Indian Head in 2005 and 2007 and at Scott in 2005 would justify topdressing N. In order for the application to be profitable, increases in yield must be sufficiently large to cover the costs of both the N fertilizer and the added field operation. The average potential N fertilizer savings in for the VRN treatments ranged from 20-56 kg N ha^{-1} and within each site-year and algorithm, the recommended N rates varied by 2-47 kg ha^{-1}. Overall, an average of 38 kg ha^{-1} less fertilizer N was applied in the VRN treatment than in the FPN/SFN treatments. For 2006 and 2007, when both variations of the N application algorithm were evaluated, the average amounts of topdressed N were 9 kg N ha^{-1} for VRN1 and 14 kg N ha^{-1} for VRN2.

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

Nitrogen management affected grain yields at all site-years except for Scott in 2007. The unfertilized checks yielded lower than the combined fertilized treatments at all site-years ($P<0.001$) except Scott in 2007 where the unfertilized check tended to yield lower, but was only significant at $P=0.086$ (Table 34). Mean grain yields of the check plots ranged from 992-2087 kg ha^{-1}, or 59-80% of highest yielding fertilized treatment. There were no cases where the NR treatment yielded significantly higher than the FPN treatment, indicating that 100-116 kg fertilizer N ha^{-1}, or approximately 150 kg total N ha^{-1} (soil plus fertilizer) was typically sufficient to achieve maximum canola yields. However, at Indian Head in 2007, the NR treatment yielded substantially higher than the next highest treatment, and although generally not significantly higher than the other fertilized treatments individually, the NR treatment yielded higher than the combined RRN, SFN, and VRN treatments ($P=0.008$).

While there was no definite evidence of a yield response to the topdressed N at either location in 2005 or 2006, at Scott 2006 the SFN treatment had the highest mean yield overall. At Indian Head, the RRN treatment yielded the same as the SFN and VRN treatments in both years, indicating that there was no yield response to topdressed N. In 2005 at Indian Head, because the RRN treatment also yielded the same as the FPN treatment, we attributed the apparent lack of response to topdressed N to sufficient N fertility at the reduced rates of starter N. In 2007 at Indian Head, even though we applied essentially no N in the topdress application, the combined VRN treatments yielded higher than the RRN treatment, which was presumably a function of spatial variability. At Scott in 2007 the overall response to N fertilizer was very weak; thus, although an RRN treatment was not included to verify this assumption, it is unlikely that there was a yield response to post-emergent N at this site-year.

That both the NR and FPN treatments yielded higher than the combined split N treatments at Indian Head 2005 suggests that N availability limited grain yields in the split N treatments to some extent at this site-year. In 2006 at Indian Head, the FPN treatment yielded 376 kg ha^{-1} higher than the RRN treatment and the RRN, SFN, and VRN treatments yielded the same as one another. The dry conditions following the topdress N applications may have restricted movement of the UAN into the rooting zone and increased the potential for volatile NH_3 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. (2007) showed that topdressing UAN is not an effective method of supplying N to crops under prolonged dry conditions. In 2007 at Indian Head, the VRN, SFN and FPN treatments all had similar yields to one another, despite the fact that the VRN treatment received 33 kg N ha^{-1} less fertilizer N in total. Again, the yield of the RRN treatment tended to be lower than for the other fertilized treatments and was significantly lower than the FPN treatment in addition to the combined VRN treatments (P=0.036). That the VRN treatment did not yield differently from the treatments that received more N, despite yielding higher than the RRN treatment demonstrates the ability of the sensor measurements to account for spatial variability in crop status. At Scott in 2007, although substantial responses to topdressed N were predicted, it is probable that the hot, dry conditions in July hastened maturity and reduced the overall responsiveness to N. Furthermore, the actual yield of the NR treatment at Scott in 2007 (1419 kg ha^{-1}) was much lower than the predicted yield of 4933 kg ha^{-1}.

While the VRN treatment at Scott in 2005 did not yield significantly different from either the SFN or FPN 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 there being no difference in NDVI between the two treatments, the NR treatment yielded 455 kg ha^{-1} higher than the VRN treatment at this site-year. Recall that the plots at this site were severely damaged by wind and hail while in full bloom. It is conceivable that the additional vegetative growth required for the plots to recover from the hail damage increased the plant's total N requirements. As such, the additional 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 VRN treatment received 24 kg ha^{-1} less fertilizer N than the FPN treatment at Scott in 2005 and the two treatments did not yield differently from one another, yield was not maximized in either treatment. At Scott in 2006, the VRN treatments yielded the same as the FPN and NR treatments, but lower than the SFN treatment. The VRN treatment performed well overall at Indian Head in 2005 and 2007, where yields were not significantly different from the FPN treatment, despite having received 53 and 33 kg ha^{-1} less N, respectively.

In 2006 and 2007, where we tested the two variations of the algorithm, there was no apparent advantage to adjusting the yield potential equation upwards by 33%. While 5 kg N ha^{-1} more N was recommended using the adjusted curve (VRN2) on average compared the VRN1 treatment, the two treatments always yielded the same. As such, there was no evidence that adjusting the yield potential curves upwards improved the estimates of N topdressing requirements and, based on the current results, we have no reason to recommend the adjustment.

Table 36. Grain yields of canola grown under various N management strategies at Indian Head and Scott for the 2005, 2006 and 2007 growing seasons.

	Indian Head			Scott		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Nitrogen Management	kg ha^{-1}					
Check	2087b	1481d	1480c	1713c	992b	1434
N Rich (NR)	3052a	2312ab	2517a	2550a	1419a	1783
Farmer Practice (FPN)	2958a	2389a	2051abc	2294ab	1479a	1693
Reduced N (RRN)	2731a	2014bc	1711bc	na	na	na
Split / Fixed (SFN)	2718a	2000bc[y]	2399ab	2271ab	1543a	1560
Variable Rate 1 (VRN1)	na	1935c	2177abc	na	1402a	1673
Variable Rate 2 (VRN2)	2776a	2019bc	2176abc	2095bc	1328a	1634
	Analysis of Variance					
Source	p > F					
Treatment	**	**	**	**	**	ns
Replicate	ns	ns	ns	ns	[v]	*
Residual C.V. (%)	6.5	7.7	14.6	10.0	10.3	13.4
	Selected Contrasts p-value					
Check vs Rest	**	**	**	**	**	ns
NR vs RRN+SFN+VRN[x]	**	**	*	*	ns	ns
FPN vs RRN+SFN+VRN[x]	*	**	ns	ns	ns	ns
VRN vs NR[w]	*	**	ns	*	ns	ns
VRN vs FPN[w]	ns	**	ns	ns	ns	ns
VRN vs SFN[w]	ns	ns	ns	ns	ns	ns
VRN vs RRN	ns	ns	*	na	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]SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment
[x]RRN treatment excluded from contrast at Scott
[w]Contrasts include both VRN 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; *significant at $0.01 \le p \le 0.05$; **significant at $p < 0.01$

Nitrogen management affected grain N concentrations at four of the six site-years (Table 35). Excluding Scott 2005, where grain N was determined using an NIR instrument, mean grain N concentrations ranged from 30.6-39.8 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 VRN 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 observed grain N concentration of the NR treatment was significantly higher than for the combined split N treatments at all site-years except Indian Head in 2007 while that of the FPN treatment was only greater than the split N treatments at Indian Head in 2006 and Scott in 2007, suggesting that fertilizer

N does not greatly affect grain N concentrations until the amount of N applied exceeds crop demands. The grain N concentrations observed in the unfertilized check treatment were lower than those of the combined fertilized treatments at both locations in 2006, but neither in 2005 and Scott only in 2007. Malhi and Gill (2007) found that fertilizer N did not typically cause grain protein concentrations to increase until the amount applied approached 75-100 kg N ha^{-1}. Furthermore, increased yields with fertilizer N can having a diluting effect, sometimes causing grain protein concentrations to decrease when low rates of N are applied (Malhi and Gill 2007). In other research, grain N concentrations increased linearly with N rate beyond 40 kg N ha^{-1} (Malhi and Gill 2004) and increases in grain N have been reported at rates as low as 25 kg N ha^{-1} (Hocking et al. 2002).

Table 37. Grain N concentrations of canola grown under various N management strategies at Indian Head and Scott in the 2005, 2006 and 2007 growing seasons. Grain N was determined using the Kjeldahl method at all site-years except for Scott 2005 where an NIR instrument was used and Indian Head in 2006 and 2007 where a LECO protein analyzer was used.

	Indian Head			Scott		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Nitrogen Management	g N kg^{-1}					
Check	33.7	31.9cd	38.0	40.6bc	30.6c	34.1c
N Rich (NR)	37.1	37.8a	41.8	42.3a	37.0a	40.7a
Farmer Practice (FPN)	34.5	34.8b	40.2	40.7bc	35.2ab	38.4b
Reduced N (RRN)	32.9	33.9bc	38.5	na	na	na
Split / Fixed (SFN)	35.8	31.8cd[y]	41.5	41.2ab	36.6a	37.0b
Variable Rate 1 (VRN1)	na	31.3d	39.8	na	33.3b	36.7b
Variable Rate 2 (VRN2)	33.9	32.6cd	38.5	40.0c	33.3b	37.1b
	Analysis of Variance					
Source	p > F					
Treatment	ns	**	ns	**	**	**
Replicate	ns	**	ns	**	[v]	**
Residual C.V. (%)	5.8	2.81	6.9	1.58	2.82	3.09
	Selected Contrasts					
	p-value					
Check vs Rest	ns	**	ns	ns	**	**
NRvs RRN+SFN+VRN[x]	*	**	ns	**	**	**
FPNvsRRN+SFN+VRN[x]	ns	**	ns	ns	ns	*
VRN vs NR[w]	*	**	ns	**	**	**
VRN vs FPN[w]	ns	**	ns	ns	**	*
VRN vs SFN[w]	ns	ns	ns	*	**	ns
VRN vs RRN	ns	**	ns	**	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]SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment
[x]RRN treatment excluded from contrast at Scott
[w]Contrasts include both VRN 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; *significant at $0.01 \le p \le 0.05$; **significant at $p < 0.01$

While the only site-years where grain protein concentrations for the FPN treatment were significantly higher than the combined treatments was Indian Head in 2006 and Scott in 2007, grain protein concentrations in the NR treatment were significantly higher than those of the combined RRN, SFN, and VRN treatments in all but one case, the exception being Indian Head in 2007. Higher grain N concentrations were observed for the SFN treatment at Scott in 2006, but at Indian Head there was no difference. Grain N concentrations of the SFN treatment were higher than those of the VRN treatment in both 2005 and 2006 at Scott, but this did not occur at Indian Head.

Table 38. Grain N yields (kg N ha^{-1}) of canola grown under various N management strategies at Indian Head and Scott in 2005, 2006, and 2007. Grain N was determined using the Kjeldahl method at all site-years except for Scott 2005 where an NIR instrument was used and Indian Head in 2006 and 2007 where a LECO protein analyzer was used.

	Indian Head			Scott		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Nitrogen Management			kg N ha^{-1}			
Check	70.1c	47.3c	57.2c	69.7c	30.4c	49.1b
N Rich (NR)	113.2a	87.6a	105.5a	107.6a	52.6ab	71.1a
Farmer Practice (FPN)	102.2ab	83.4a	81.8abc	93.7ab	52.1ab	64.1ab
Reduced N (RRN)	89.8b	68.1b	65.5bc	na	na	na
Split / Fixed (SFN)	97.2b	63.7b[y]	99.7ab	93.6ab	56.4a	57.1ab
Variable Rate 1 (VRN1)	na	60.3b	86.9abc	na	46.8ab	60.6ab
Variable Rate 2 (VRN2)	94.1b	65.8b	abc	84.3bc	44.2b	60.2ab
			Analysis of Variance			
Source			p > F			
Treatment	**	**	**	**	**	*
Replicate	ns	ns	ns	*	[v]	ns
Residual C.V. (%)	7.8	9.8	17.4	9.9	11.2	13.8
			Selected Contrasts			
			p-value			
Check vs Rest	**	**	**	**	**	**
NRvsRRN+SFN+VRN[x]	**	**	*	**	ns	*
FPNvsRRN+SFN+VRN[x]	ns	**	ns	ns	ns	ns
VRN[w] vs NR	**	**	ns	**	*	ns
VRN vs FPN	ns	**	ns	ns	ns	ns
VRN vs SFN	ns	ns	ns	ns	**	ns
VRN vs RRN	ns	ns	*	na	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]SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment; [x]RRN treatment excluded from contrast at Scott; [w]Contrasts include both VRN 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; *significant at 0.01 ≤ p ≤ 0.05; **significant at p < 0.01

Applying N fertilizer increased the grain N yields (kg N ha^{-1}) at all site-years, with less grain N always harvested from the unfertilized check than from the combined fertilized treatments (Table 36). The absolute quantities of N removed in the canola seed ranged from 30 kg N ha^{-1} at Scott in 2006 to 113 kg N ha^{-1} at Indian Head in 2005 and the patterns of grain N yields resembled those observed for grain yield (Table 34). The highest grain N yields were observed for the NR treatment at all site-years except Scott 2006, where both N yields and grain yields were highest in the SFN treatment. However, grain N yields in the NR treatment were never significantly higher than for the FPN treatment, suggesting that the efficiency of the applied N decreased at N rates exceeding those applied in the FPN treatments. Due to the difference in grain yield, significantly less grain N was harvested from the RRN treatment than for the combined VRN treatments at Indian Head in 2006 (P=0.036).

According to the overall F-tests, N management significantly affected fall residual soil NO_3-N levels for the 0-60 cm soil depth at Indian Head in 2005 and 2006 and of the study and at Scott in 2006 and 2007 (Table 37). While the data from Scott in 2005 was highly variable, the mean fall residual NO_3-N levels of both the SFN and NR treatments tended to be higher than for any other treatments. Because of the large quantities of N applied, residual NO_3-N levels in the NR treatment at Indian Head were always higher than the combined split N treatments. Although the F-test was not significant at Indian Head in 2007, residual NO_3-N levels in the NR treatment were significantly higher than the combined split N treatments (P=0.010) and the VRN treatments on their own (P=0.018). Residual NO_3-N levels of the VRN and FPN treatments tended to be similar to one another other and the levels of the FPN treatment were never higher than the combined split N treatments, indicating that fall soil NO_3-N does not accumulate until the amount of N exceeds those required for maximum yield. 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 0-50 cm soil profile, further increases to 200 kg N ha^{-1} greatly increased residual NO_3-N levels.

Variability was relatively high for the agronomic ANUE measurements, with the observed CV values ranging from 33-70%; consequently the F-test for this variable was only significant at two site-years, Indian Head in 2005 and 2006. 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 38). The observed ANUE values fell within the ranges of values for canola reported in other studies, ranging from as low as 1.2 kg kg^{-1} at Scott in 2007 up to 15.7 kg kg^{-1} at Indian Head in 2005. In Australia under rainfed conditions, 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 decreased with increasing N rates.

Table 39. Quantity of residual NO_3-N 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, 2006 and 2007.

	Indian Head			Scott		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Nitrogen Management	kg NO_3-N ha^{-1} 0 - 60cm					
Check	20.7b	13.6b	28.2	22.7	11.2a	25.8b
N Rich (NR)	59.7a	47.2a	63.3	42.0	15.4a	63.8a
Farmer Practice (FPN)	28.7b	16.9b	35.4	24.1	9.8a	35.9b
Reduced N (RRN)	24.7b	13.7b	30.1	na	na	na
Split / Fixed (SFN)	33.5b	17.4b [y]	40.0	40.3	15.7a	30.5b
Variable Rate 1 (VRN1)	na	13.2b	30.2	na	11.5a	36.4b
Variable Rate 2 (VRN2)	28.8b	15.4b	27.0	25.4	10.1a	46.5ab
	Analysis of Variance					
Source	p > F					
Treatment	**	**	ns	ns	*	**
Bloc	ns	ns	ns	ns	y	**
Residual C.V. (%)	21.1	33.0	47.4	43.9	23.6	26.6
	Selected Contrasts p-value					
Check vs Rest	**	ns	ns	ns	ns	*
NRvsRRN+SFN+VRN[x]	**	**	*	ns	ns	**
FPNvsRRN+SFN+VRN[x]	ns	ns	ns	ns	ns	ns
VRN vs NR[w]	**	**	*	ns	*	**
VRN vs FPN[w]	ns	ns	ns	ns	ns	ns
VRN vs SFN[w]	ns	ns	ns	ns	*	ns
VRN vs RRN	ns	ns	ns	na	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] SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment
[x]RRN treatment excluded from contrast at Scott
[w]Contrasts include both VRN 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; *significant at $0.01 \le p \le 0.05$; **significant at $p < 0.01$

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 RRN 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 VRN and RRN treatments and both were higher than for any of the other treatments. In 2006 at Indian Head, ANUE of the VRN treatment was not significantly different from either the RRN or the FPN treatments. However, even though the VRN and FPN treatments had similar ANUE, the efficiency of the FPN treatment was achieved at a higher grain yield and with more fertilizer N than for the VRN treatment; thus the FPN treatment would have been more feasible from a producer's perspective. The only other significant treatment effect that was detected for

ANUE was the VRN treatment at Indian Head in 2007 having a higher ANUE than the RRN treatment, again because of the observed difference in grain yield. 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 VRN and SFN treatments tended to have the highest ANUE in 2005 and 2006 respectively. Overall, these results are consistent with those of other studies for canola where ANUE 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).

Table 40. Agronomic N use efficiency for canola grown under various N management strategies at Indian Head and Scott in 2005, 2006, and 2007.

	Indian Head			Scott		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Nitrogen Management			$kg\ kg^{-1}$			
N Rich (NR)	4.8c	4.3b	6.9	3.9	2.8	2.2
Farmer Practice (FPN)	8.7bc	8.6ab	5.7	5.0	4.1	2.5
Reduced N (RRN)	15.7a	11.2a	3.5	na	na	na
Split / Fixed (SFN)	6.3c	6.4ab	9.2	4.8	5.7	1.2
Variable Rate 1 (VRN1)	na	8.1ab	10.5	na	4.7	3.1
Variable Rate 2 (VRN2)	14.7ab	8.5ab	12.5	6.5	4.9	2.5
			Analysis of Variance			
Source			$p > F$			
Treatment	**	*	ns	ns	ns	ns
Replicate	ns	*	**	ns	[v]	**
Residual C.V. (%)	33.4	33.6	46.3	39.5	47.5	69.5
			Selected Contrasts			
			p-value			
NRvsRRN+SFN+VRN[x]	**	*	ns	ns	ns	ns
FPNvsRN+SFN+VRN[x]	ns	ns	ns	ns	ns	ns
VRN vs NR[w]	**	*	ns	ns	ns	ns
VRN vs FPN[w]	*	ns	ns	ns	ns	ns
VRN vs SFN[w]	**	ns	ns	ns	ns	ns
VRN vs RRN	ns	ns	**	na	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]SFN treatment at Indian Head in 2006 only received 82 kg N ha^{-1} in total compared with 106 kg N ha^{-1} in the FPN treatment
[x]RRN treatment excluded from contrast at Scott
[w]Contrasts include both VRN 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; *significant at $0.01 \le p \le 0.05$; **significant at $p < 0.01$

5.0 CONCLUSIONS

The overall objectives of this study were: 1) to investigate the potential for estimating canola yield potential using canola NDVI measurements early enough in the growing season to still achieve a yield response to topdressing N and 2) to evaluate the feasibility of using optical sensor measurements and high N reference crops to determine topdress N rates relative to banding the entire N requirements at the time of seeding.

Our results indicate that it is possible to estimate canola yield potential over a wide-range of environments and plant populations using in-season NDVI measurements. Similar to corn (Martin et al. 2007), NDVI increased with time as the crop progressed through the vegetative growth stages (HB2.1-2.6), peaked during the mid-reproductive stages and the start of flowering (HB3.2-4.1) and decreased to a certain extent as the crop matured. The strength of the NDVI-yield relationships followed the same temporal patterns as the absolute NDVI values; starting out weak, increasing through the vegetative growth stages until peaking between HB3.2-4.1, and often becoming weak as the crop went into full bloom. When data from multiple site-years/sensing dates were combined, dividing NDVI by one of several normalizing values typically improved the NDVI-yield relationship. Dividing NDVI by the normalizing values helps to account for differences in crop growth from one year / location to the next. The heat units all performed similarly to one another and all were an improvement over days from planting. However, dividing NDVI by days from planting is recommended when temperature data is not available. Despite the fact that the correlation coefficients for the NDVI-yield relationships were always below 0.5, we are reasonably confident in these equations considering the variability in plant populations and the multitude of factors that affect canola yields after measuring NDVI. When topdressing UAN to established canola, the N must be applied to canola prior to flowering (Lafond et al. 2008), which leaves a relatively narrow window over which yield potential can be accurately estimated and a response to topdressed N expected. However, variability in our NDVI-yield data was high because of the different seeding rates. Under optimal plant populations, NDVI measurements from approximately growth stage HB2.6 onwards should be well suited for estimating canola yield potential and potential responsiveness to topdressed N.

Overall, sensor-based N management performed well compared to the conventional practice of banding the entire estimated N requirements at seeding. The major exception was Indian Head in 2006, where mid- to late-season conditions were especially dry and, despite the large predicted response, no yield response to topdressed N was observed. Despite the lack of response to topdressed N, reducing the amount of N applied at seeding to the levels applied in the split N treatments resulted in a 380 kg ha^{-1} reduction in grain yield on average. This and, to a lesser extent, the results from Scott in 2007 indicate that soil moisture availability at the time of the topdressing must be taken into consideration. Furthermore, it may not be wise, at least in the Black soil zone, to reduce N rates at seeding below those required to achieve average yields, thus reserving topdress N applications for the fields where there is strong potential to increase yields sufficiently to cover the cost of the N application. For the remaining site-years however, no differences in yield were observed between the technology based (VRN) and benchmark (FPN) treatment and differences in NDVI tended to be small along the with recommended topdress N rates. On average, we applied 15-53% less N for the VRN treatments relative to the FPN treatment and, with the exception of Indian Head in 2006, there were no significant differences in grain yield observed between the two treatments. High variability for the agronomic N-use efficiency (ANUE) measurements made it difficult to detect differences between the various treatments. However, there was an overall tendency for ANUE to be relatively low at the high N rates and the overall mean ANUE of the VRN treatments at Indian Head was 10.9 kg grain kg N^{-1} compared with 7.7 kg kg^{-1} for the FPN treatment. Fall residual soil NO3-N levels did not typically increase until the amount of N applied greatly exceeded crop demands, thus the greatest environmental benefits of adopting this technology will arise from an overall reduction in N fertilizer use and, consequently, energy requirements in canola production with little or no reductions in overall grain production.

Sensor-based N management appears to be a feasible option for canola production in western Canada that has potential to increase ANUE over the long-term, especially in the Black soil zone. In the current economic environment however, increased efficiency alone will not provide sufficient incentive to motivate producers to adopt this technology. For the practice to be economically viable, the value of the yield gains and/or N fertilizer savings must be sufficiently large to cover the added cost of the extra field operation. Nonetheless, sensor-based N management shows potential for enhancing ANUE in canola production and, provided that the risks and benefits of benefits of sensor-based N management are managed appropriately, economic profitability for canola producers.

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APPENDIX A – SCATTER PLOTS OF VARIOUS EMPIRICAL NDVI-YIELD RELATIONSHIPS

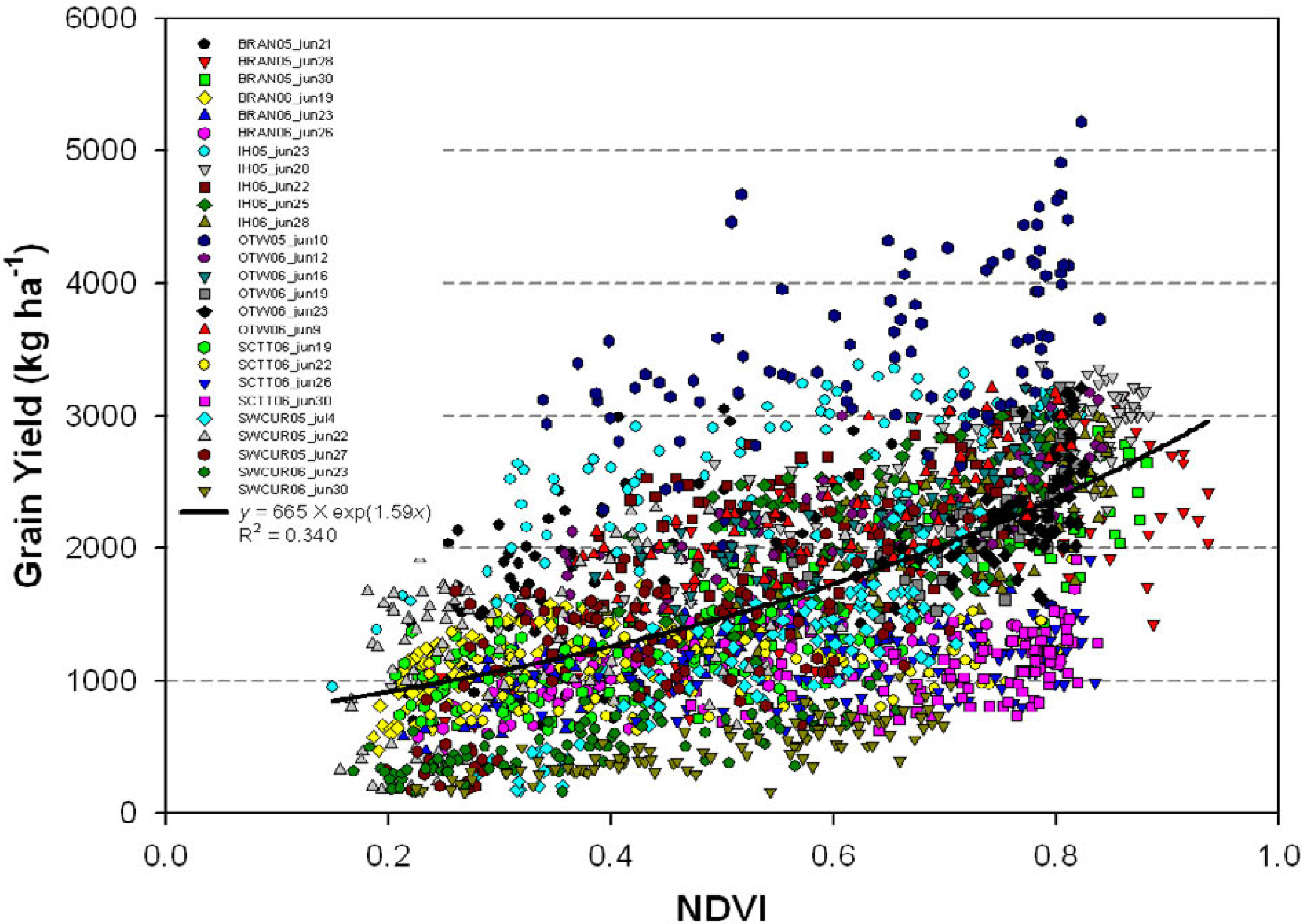

Figure A-1 Canola seed yield versus normalized difference vegetation index (R^2=0.340) for all site-years presented in Chapter 3 of Holzapfel (2007) except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

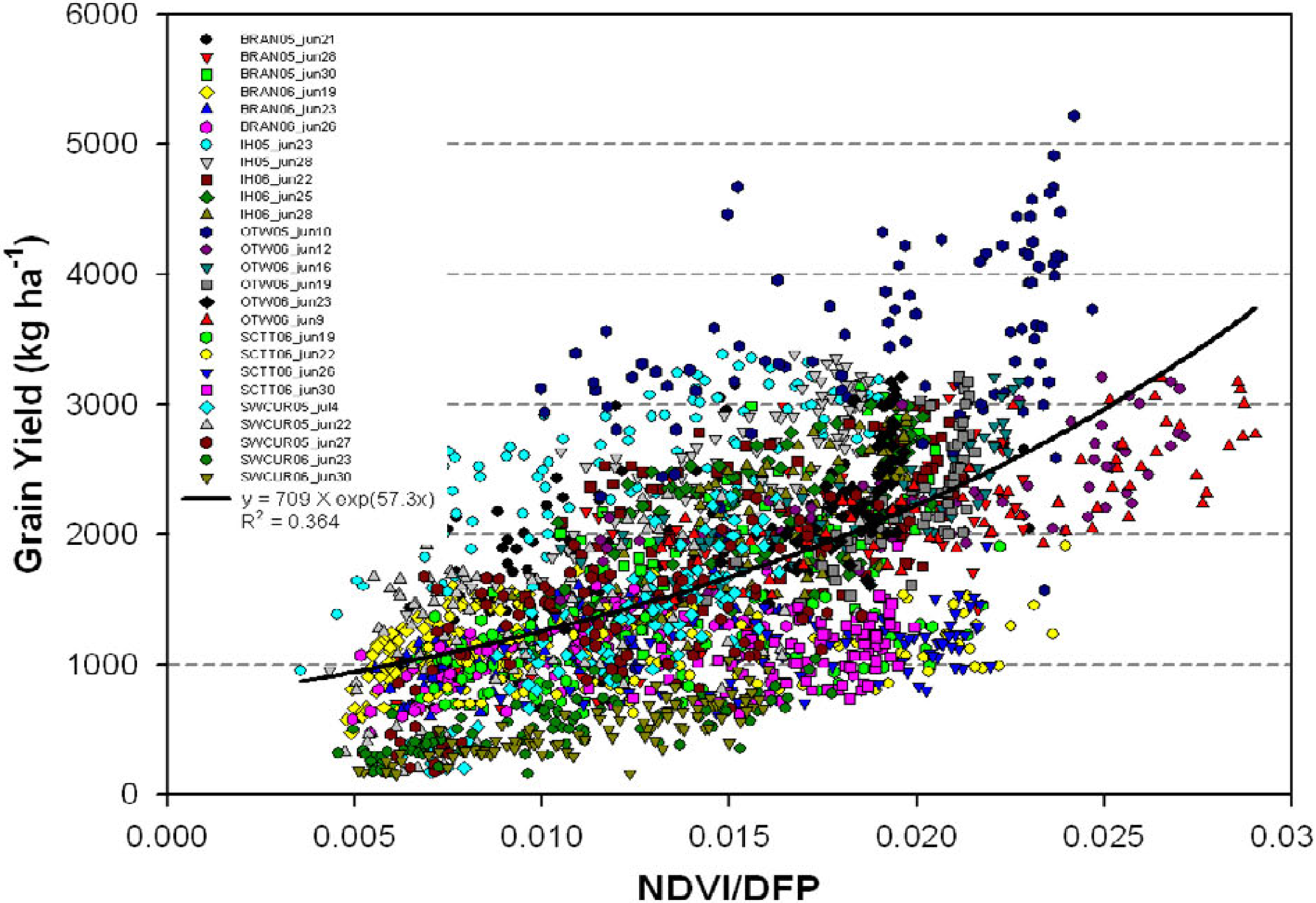

Figure A-2. Canola seed yield versus normalized difference vegetation index divided by days from planting (DFP) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

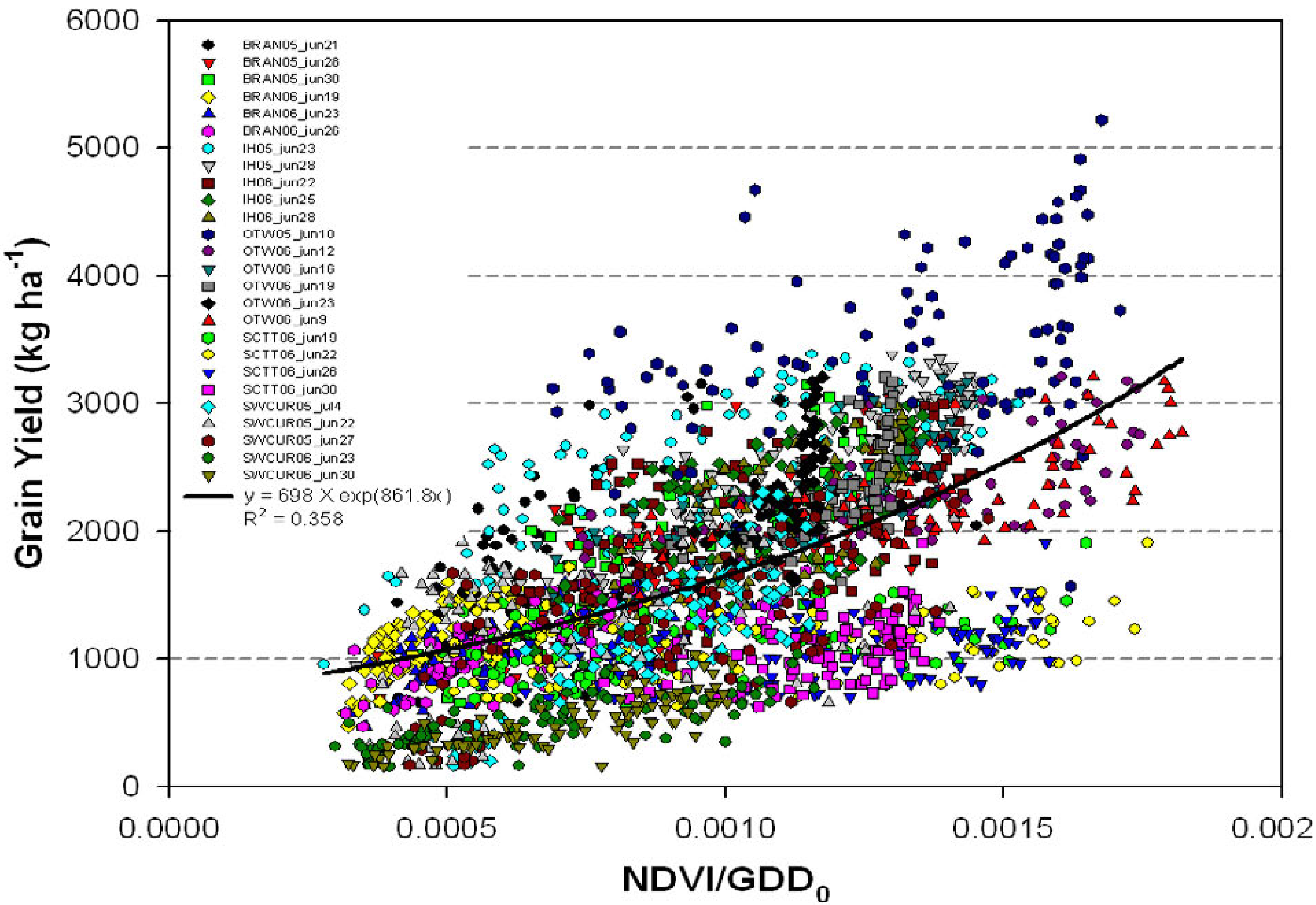

Figure A-3. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 0˚C) (GDD_0) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

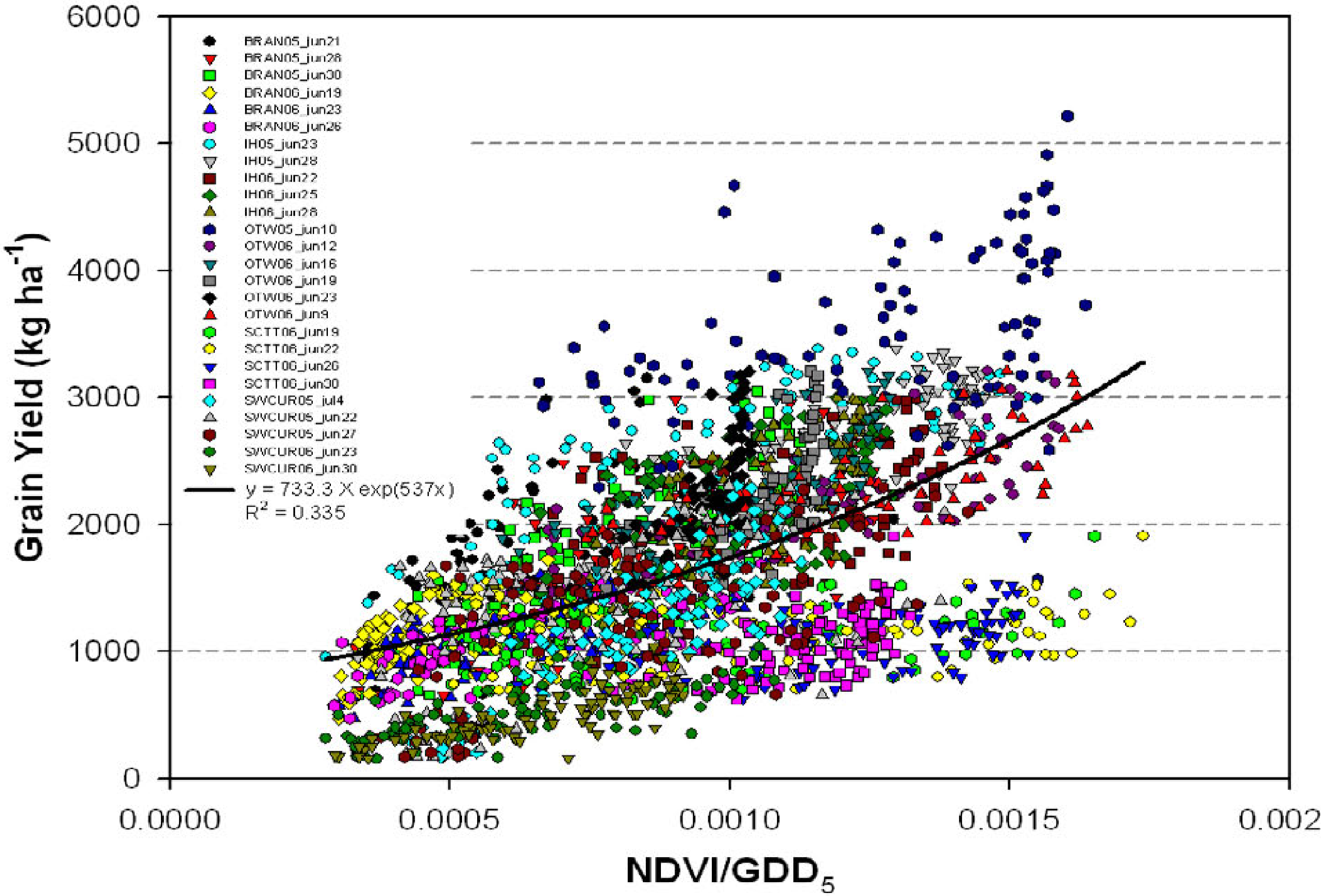

Figure A-4. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 5˚C) (GDD_5) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

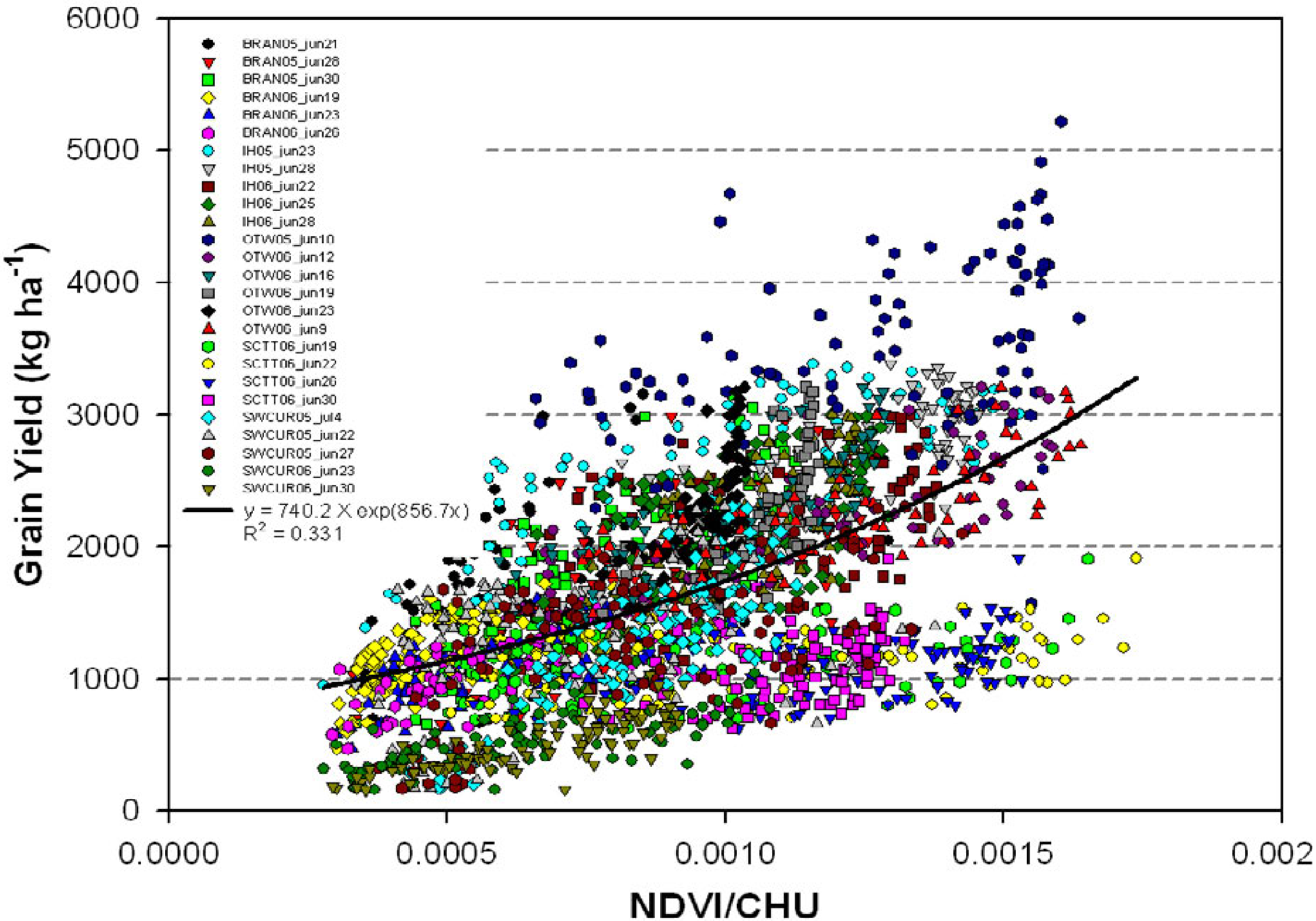

Figure A-5. Canola seed yield versus normalized difference vegetation index divided by corn heat units (CHU) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

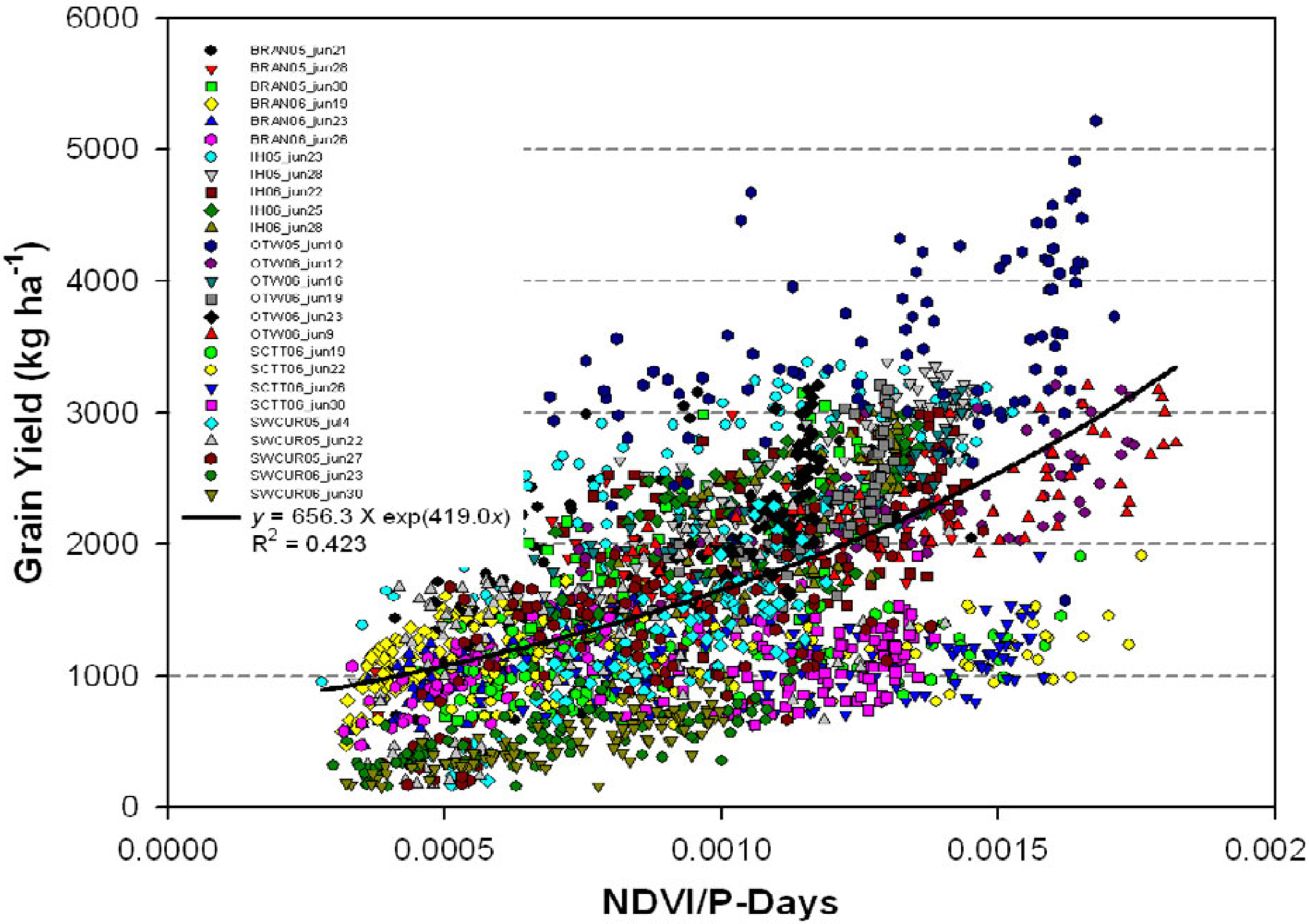

Figure A-6. Canola seed yield versus normalized difference vegetation index divided by physiological days (P-days) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

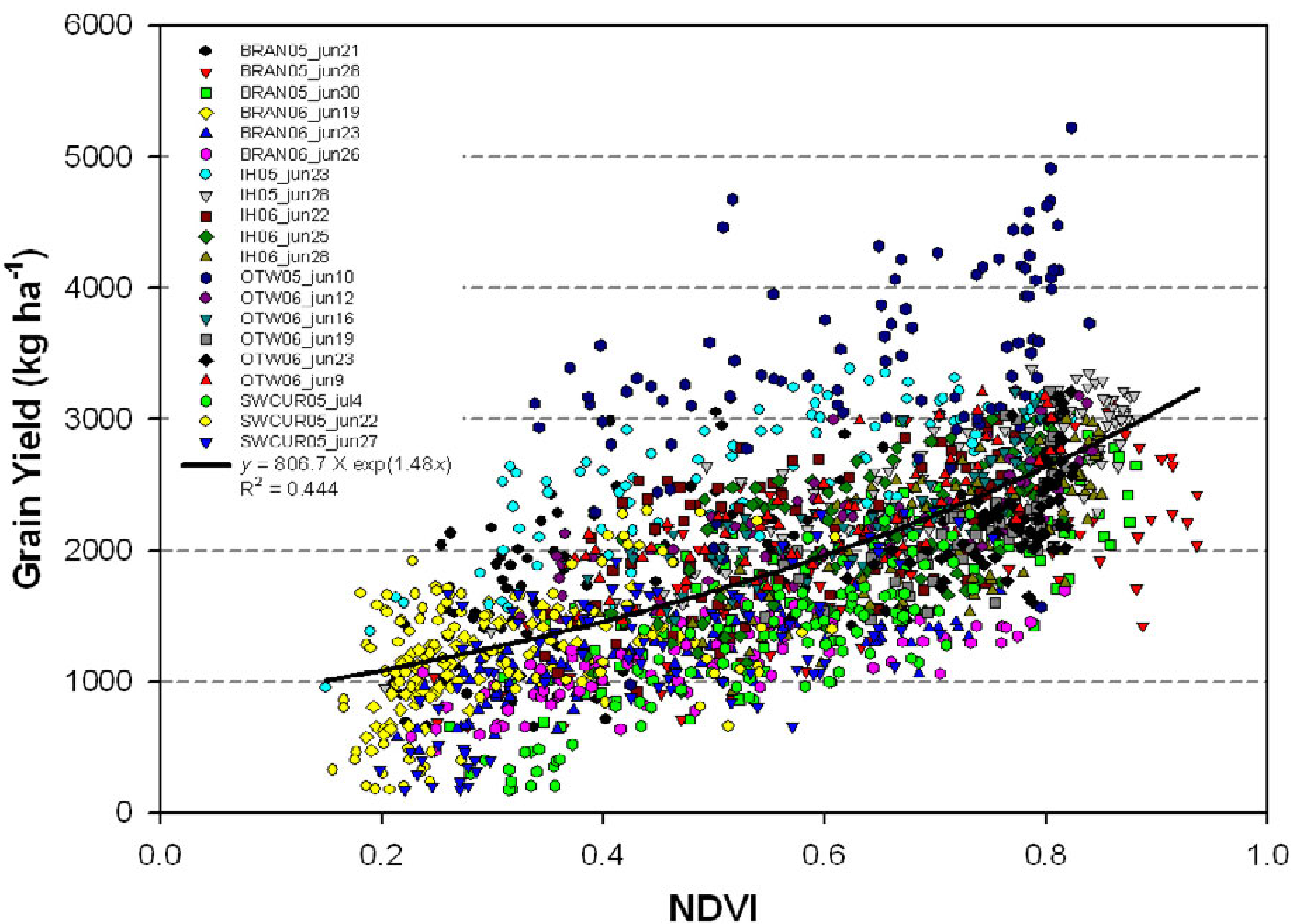

Figure A-7. Canola seed yield versus normalized difference vegetation index for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

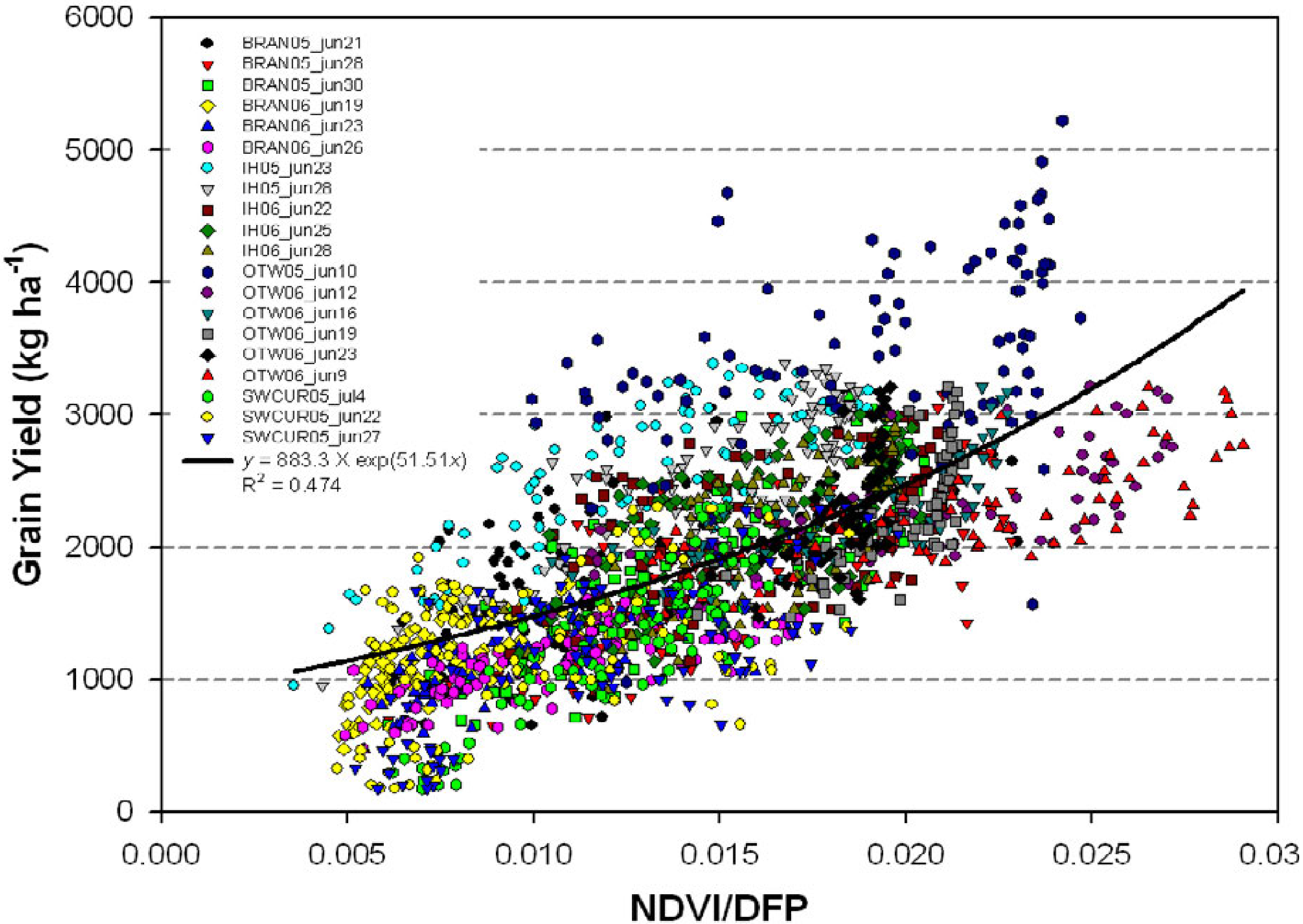

Figure A-8. Canola seed yield versus normalized difference vegetation index divided by days from planting (DFP) for all site-years in Chapter 3 of Holzapfel (2007) except for for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harper and Berkenkamp 1975).

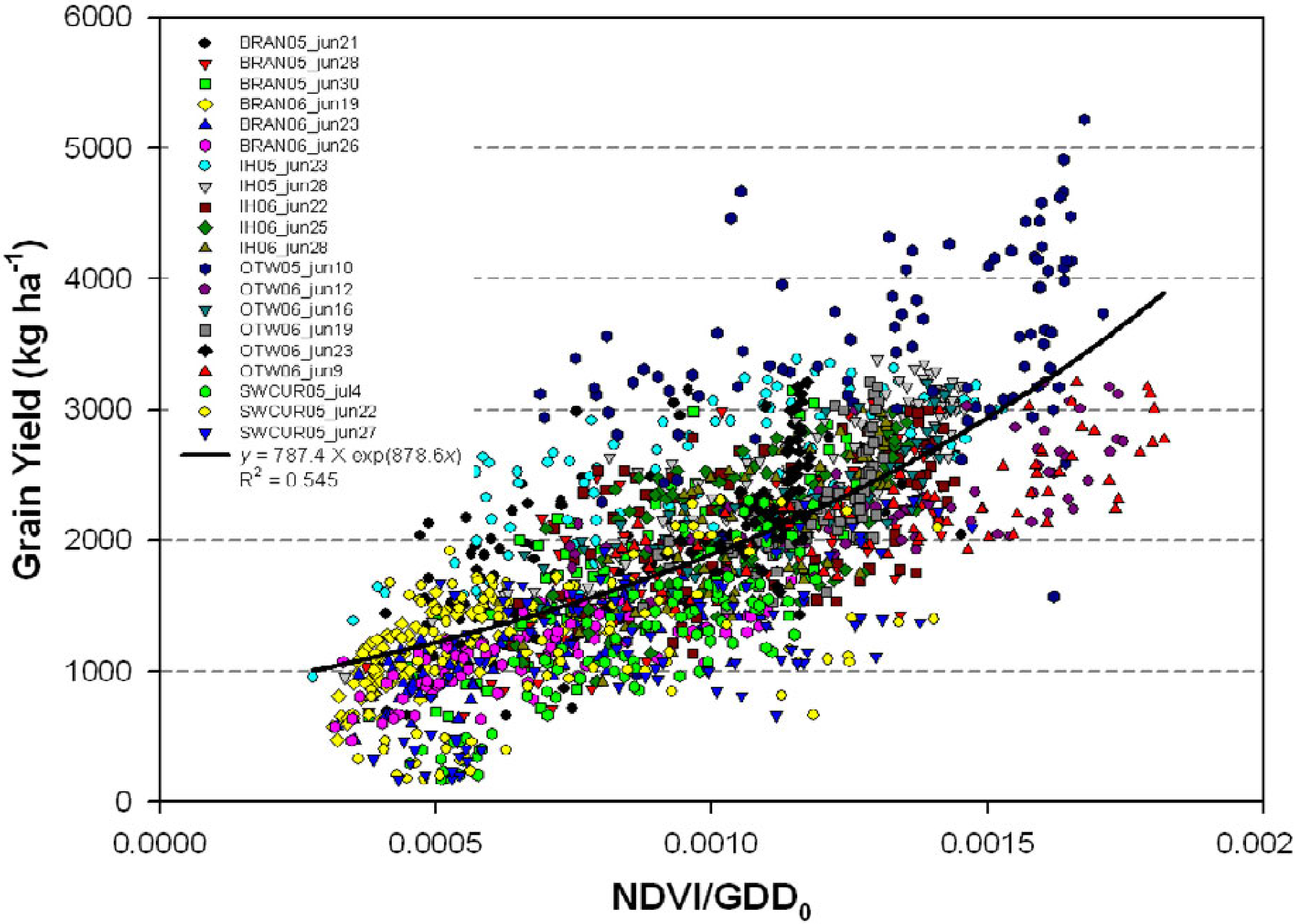

Figure A-9. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 0˚C) (GDD_0) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

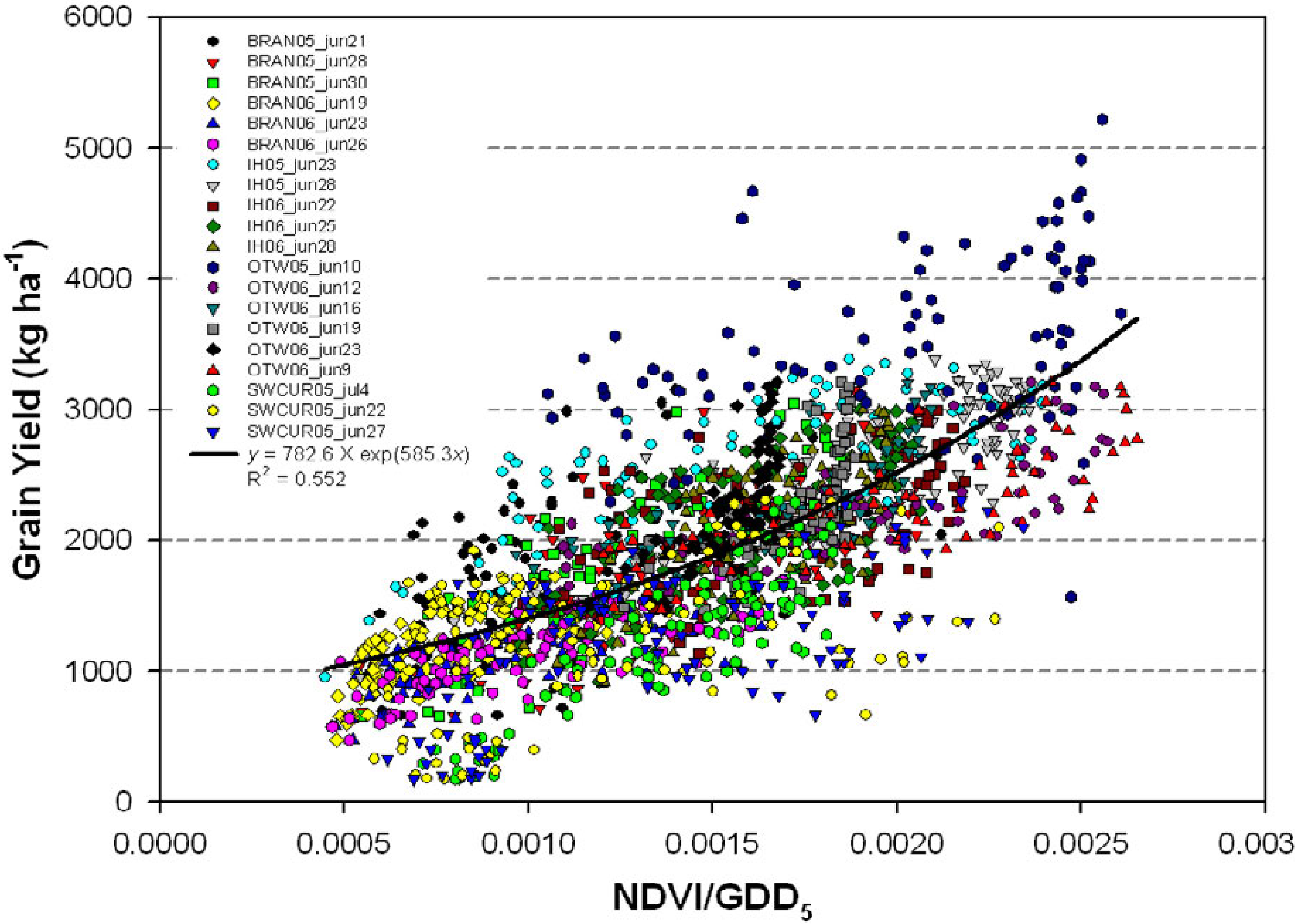

Figure A-10. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 5˚C) (GDD_5) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

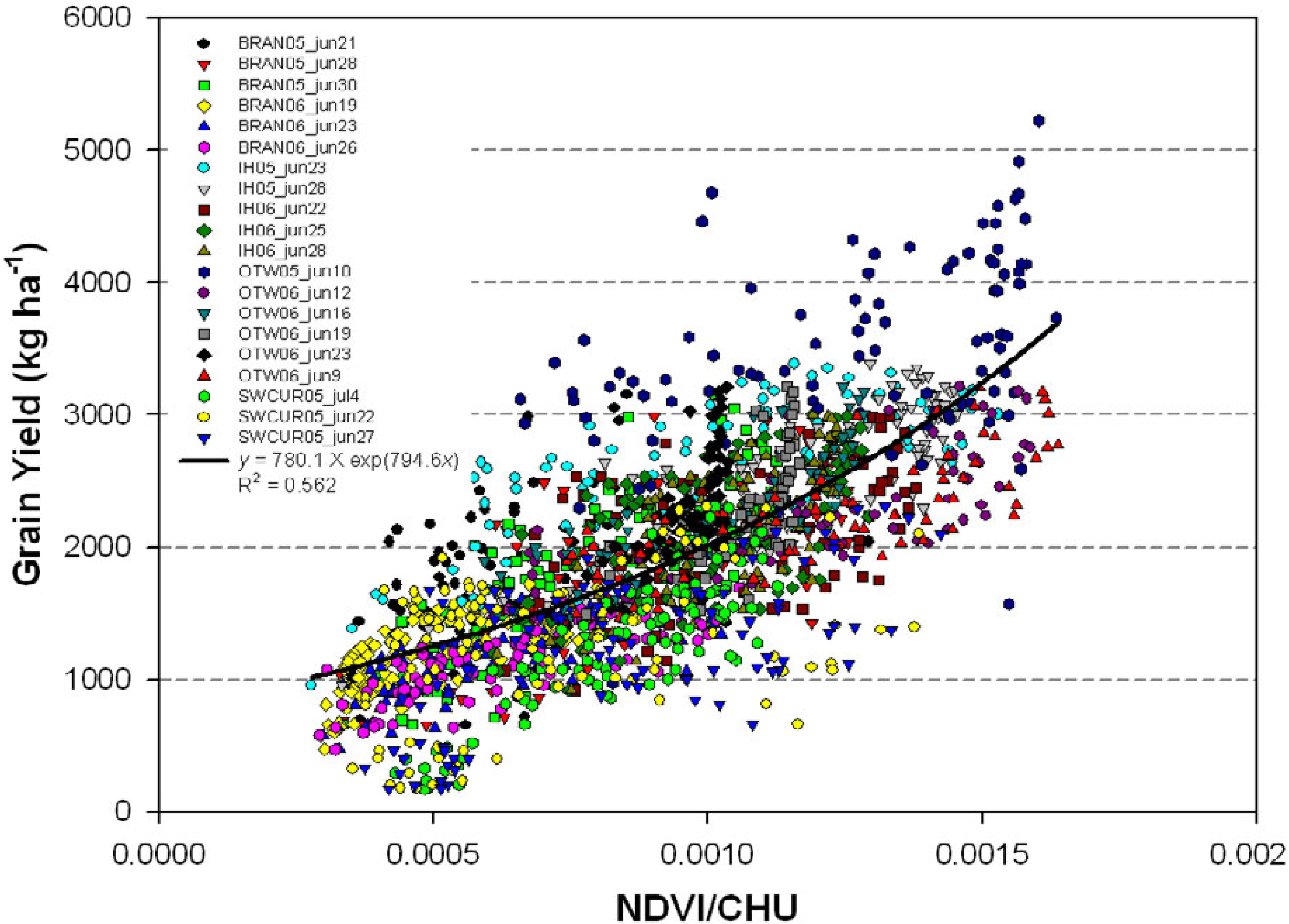

Figure A-11. Canola seed yield versus normalized difference vegetation index divided by corn heat units (CHU) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

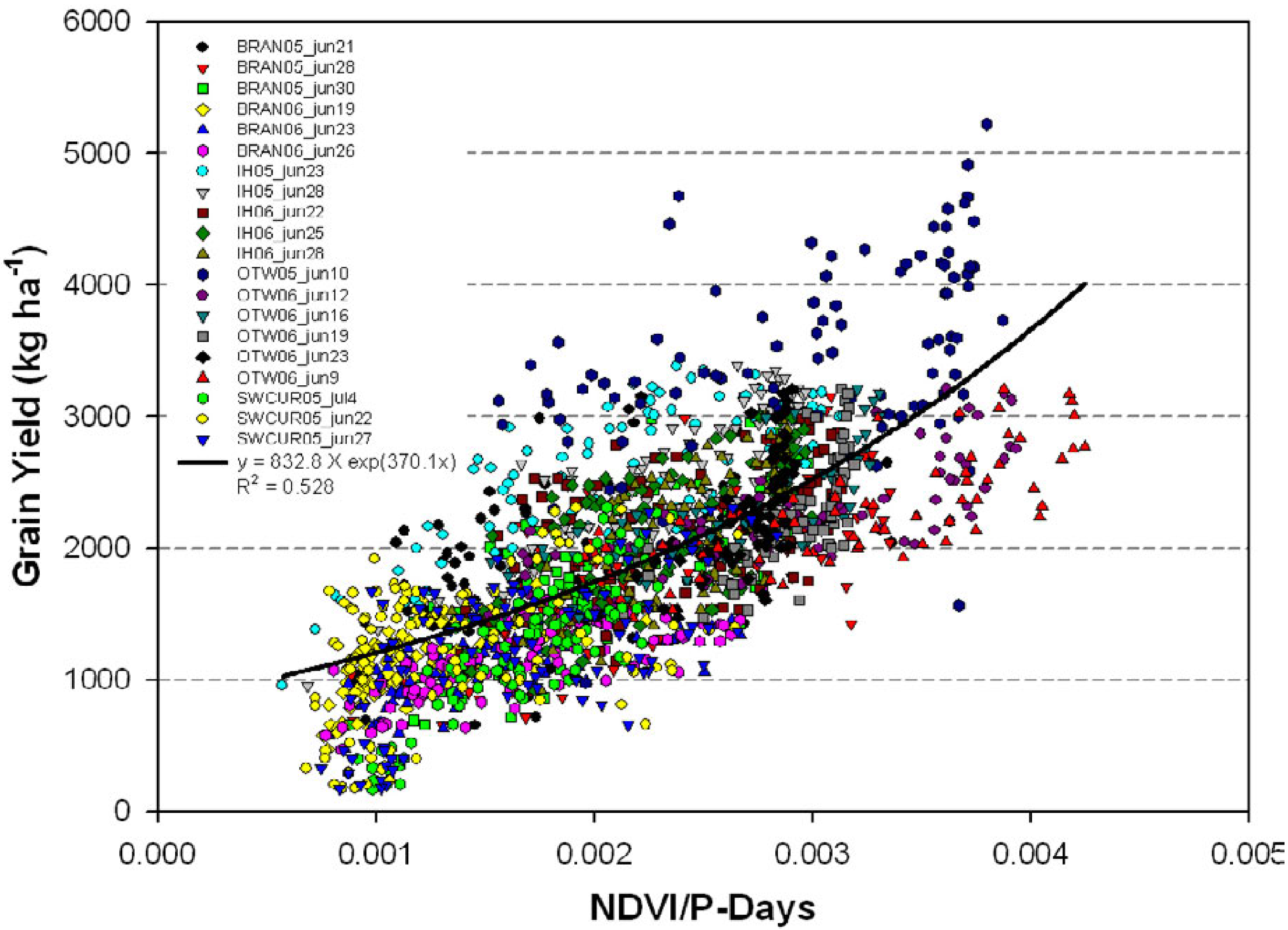

Figure A-12. Canola seed yield versus normalized difference vegetation index divided by physiological days (P-days) for all site-years in Chapter 3 of Holzapfel (2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

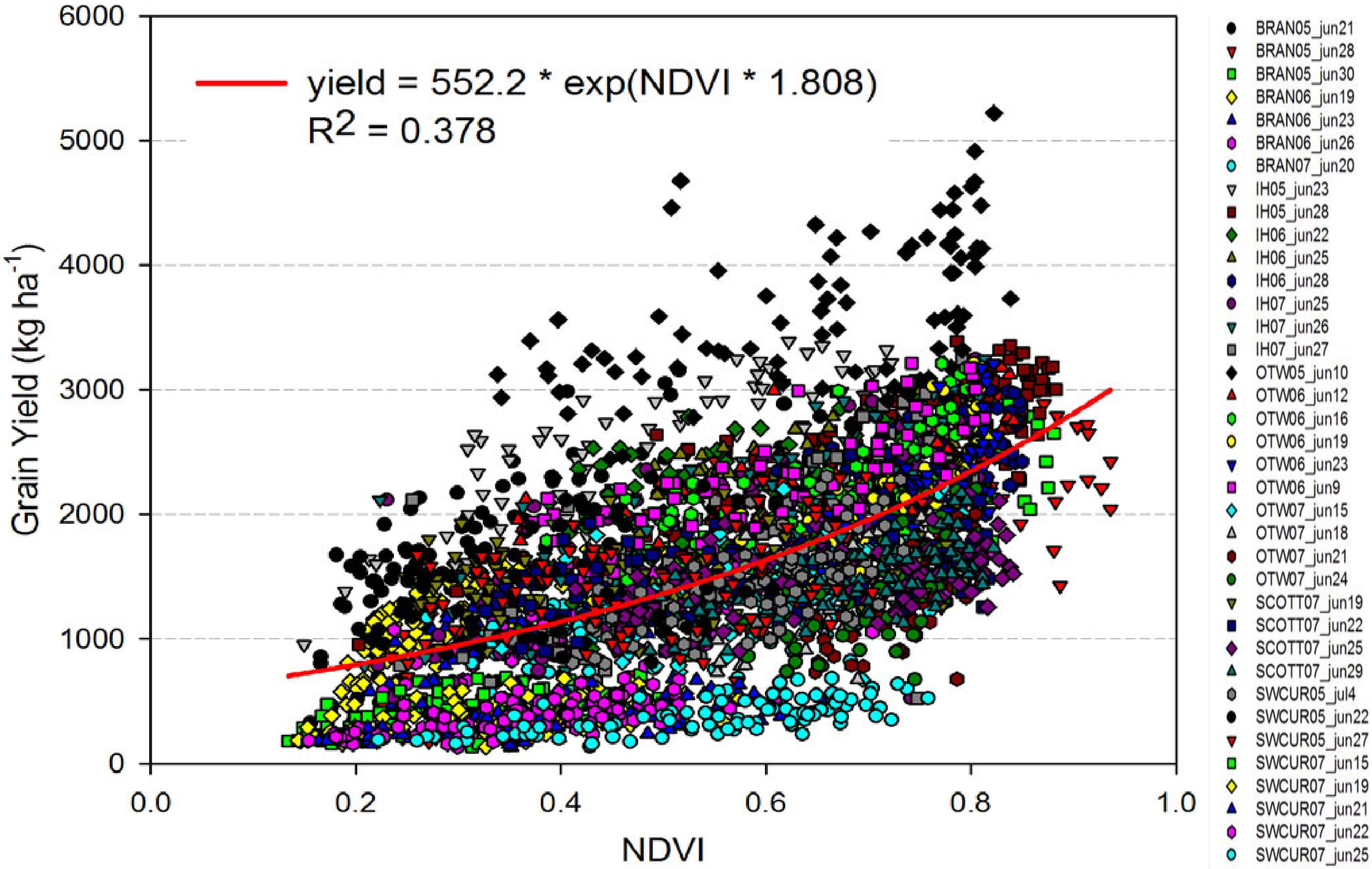

Figure A-13. Canola seed yield versus normalized difference vegetation index for all site-years (2005 – 2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

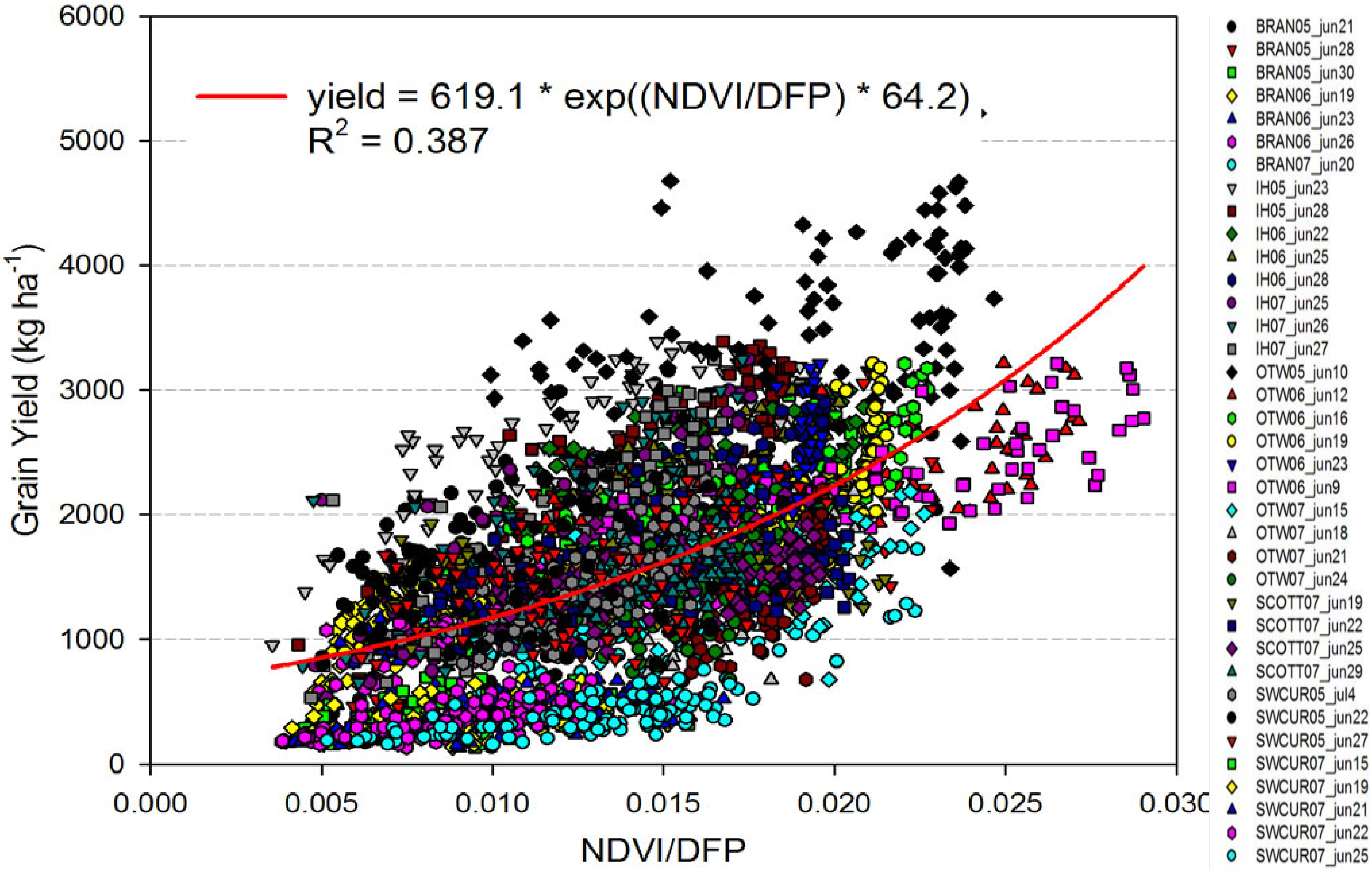

Figure A-14. Canola seed yield versus normalized difference vegetation index divided by days from planting (DFP) for all site-years (2005 – 2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

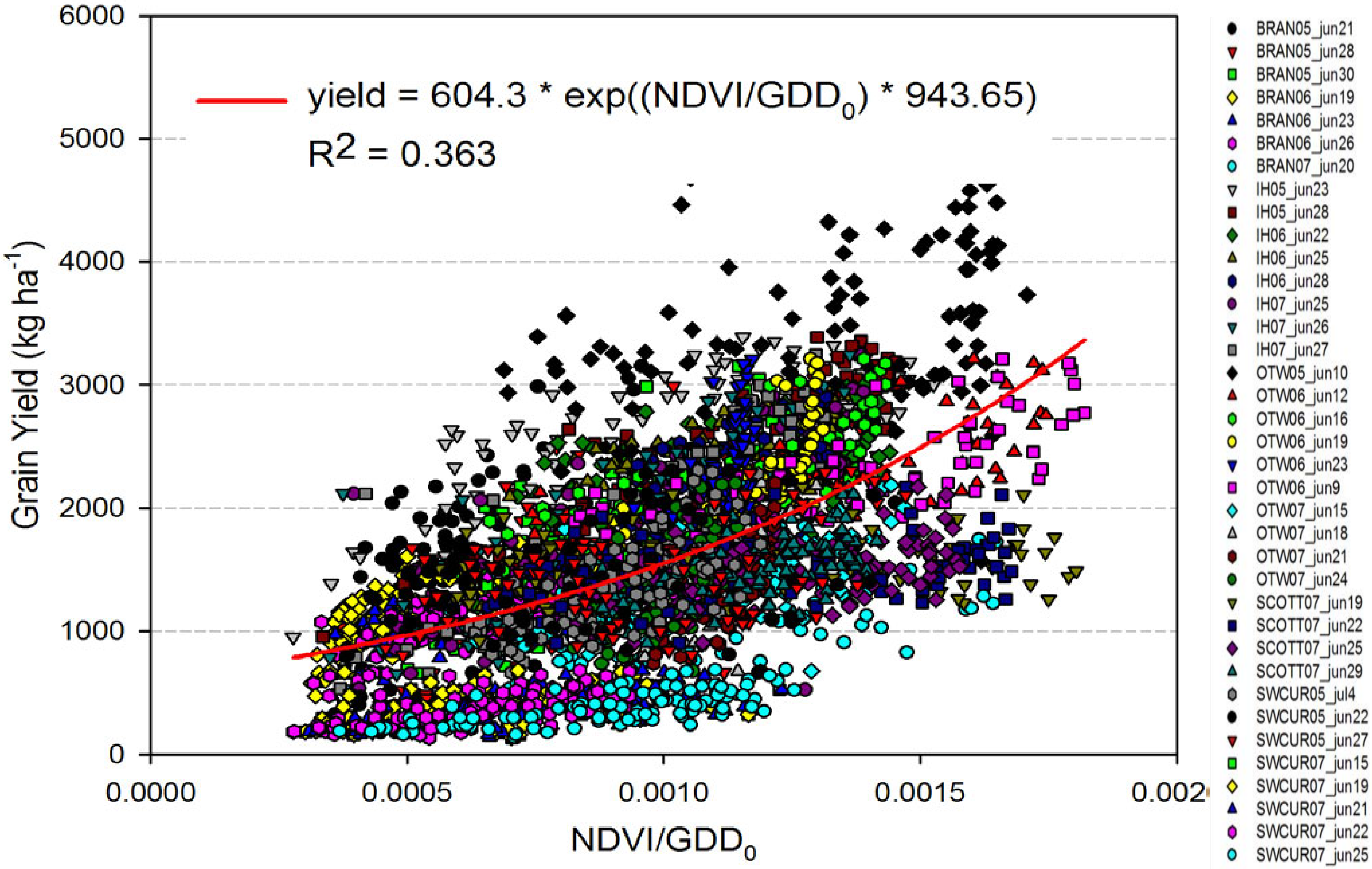

Figure A-15. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 0 ˚C) (GDD_0) for all site-years (2005 – 2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

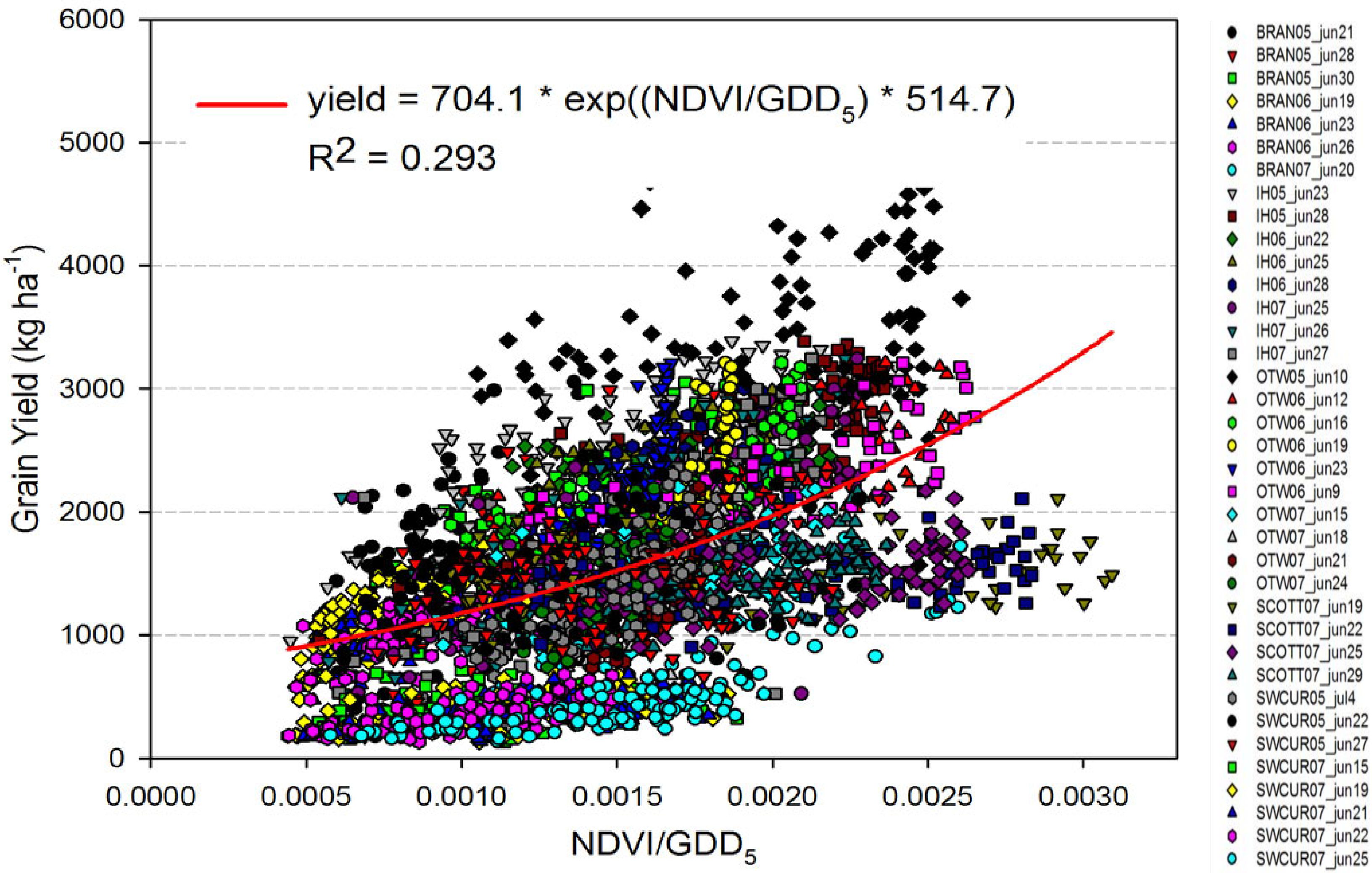

Figure A-16 Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 5 ˚C) (GDD_5) for all site-years (2005 – 2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

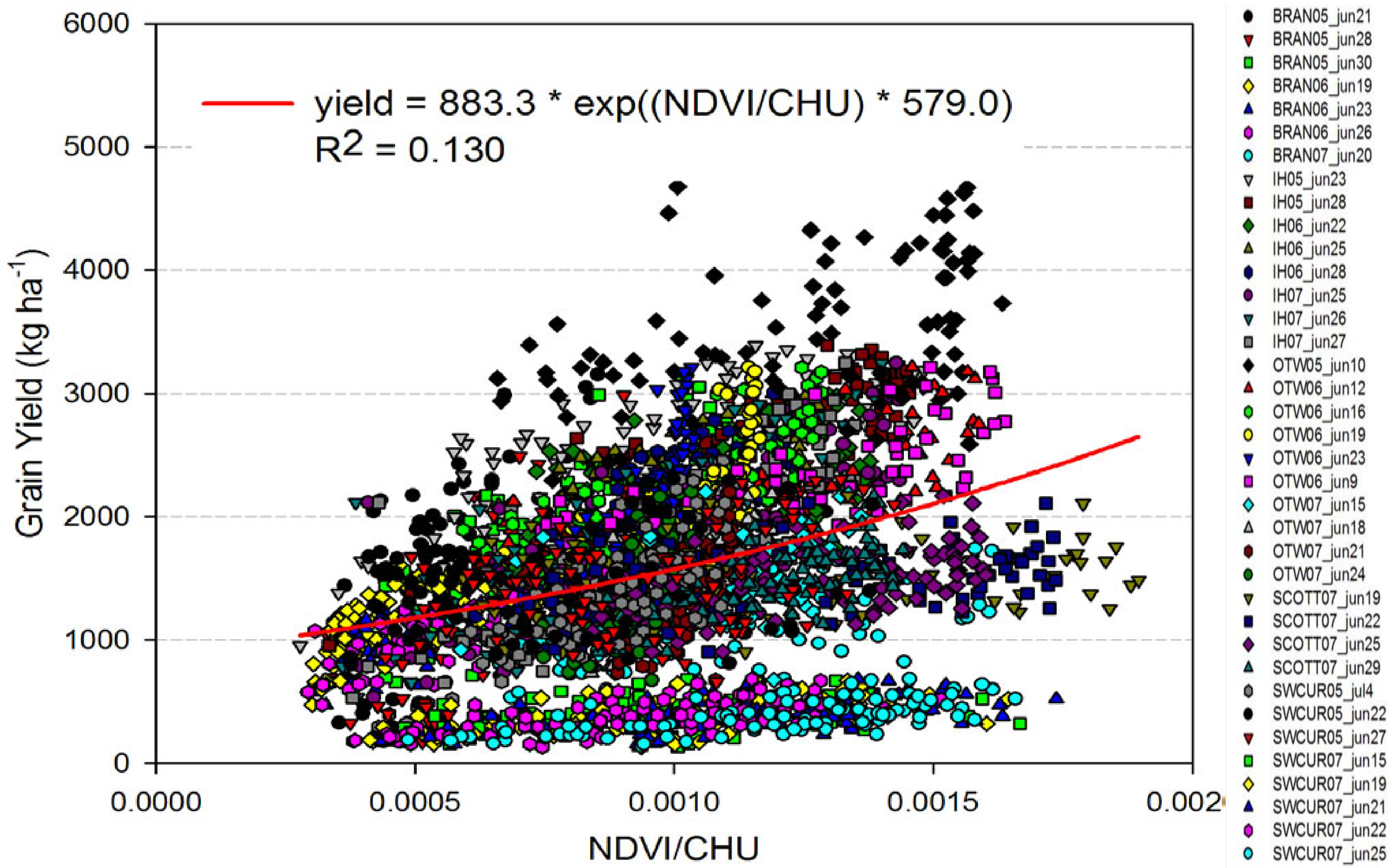

Figure A-17. Canola seed yield versus normalized difference vegetation index divided by corn heat units (CHU) for all site-years (2005 – 2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

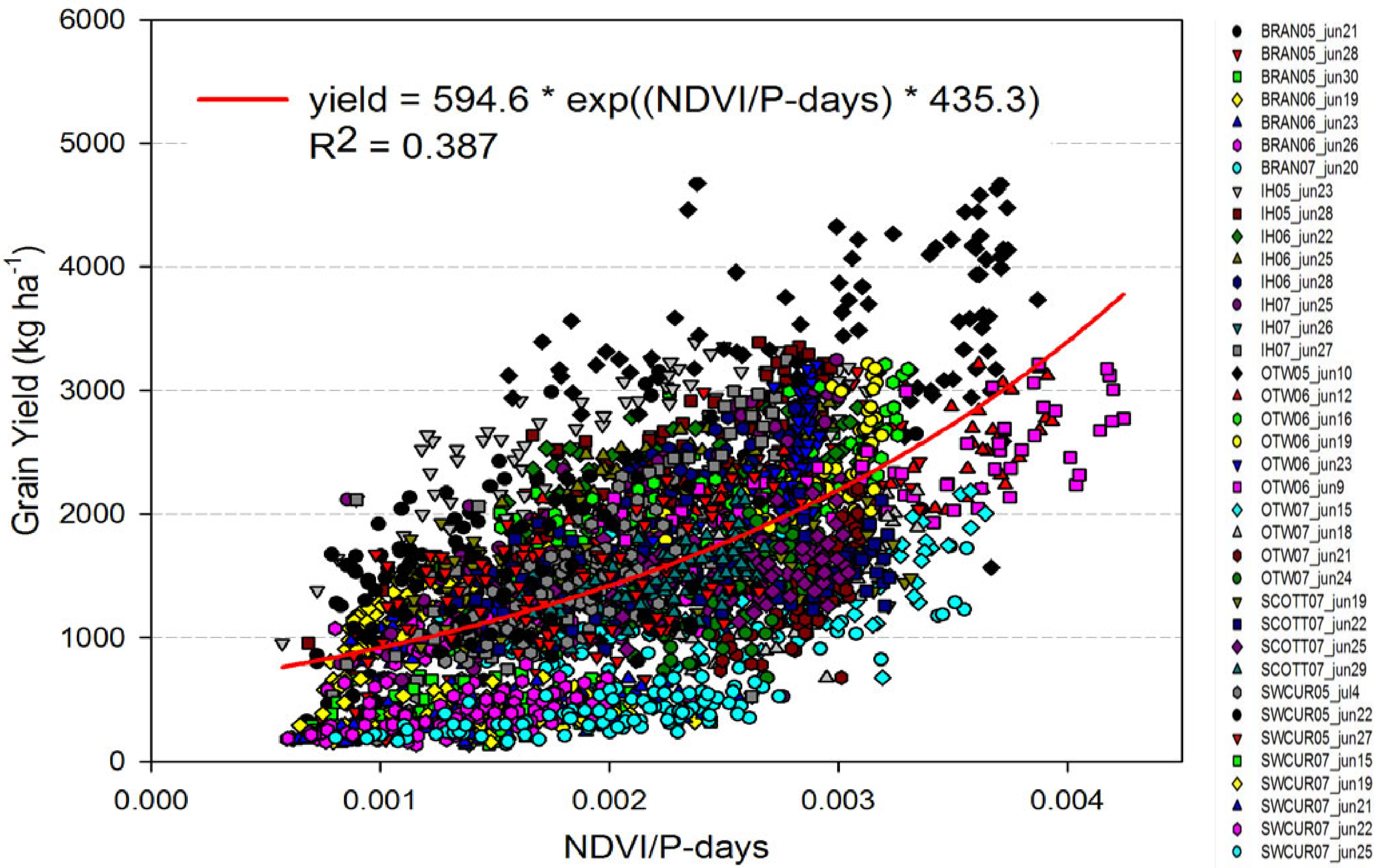

Figure A-18. Canola seed yield versus normalized difference vegetation index divided by physiological days (P-days) for all site-years (2005 – 2007) except for Scott 2005 and 2006 and Swift Current in 2006 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

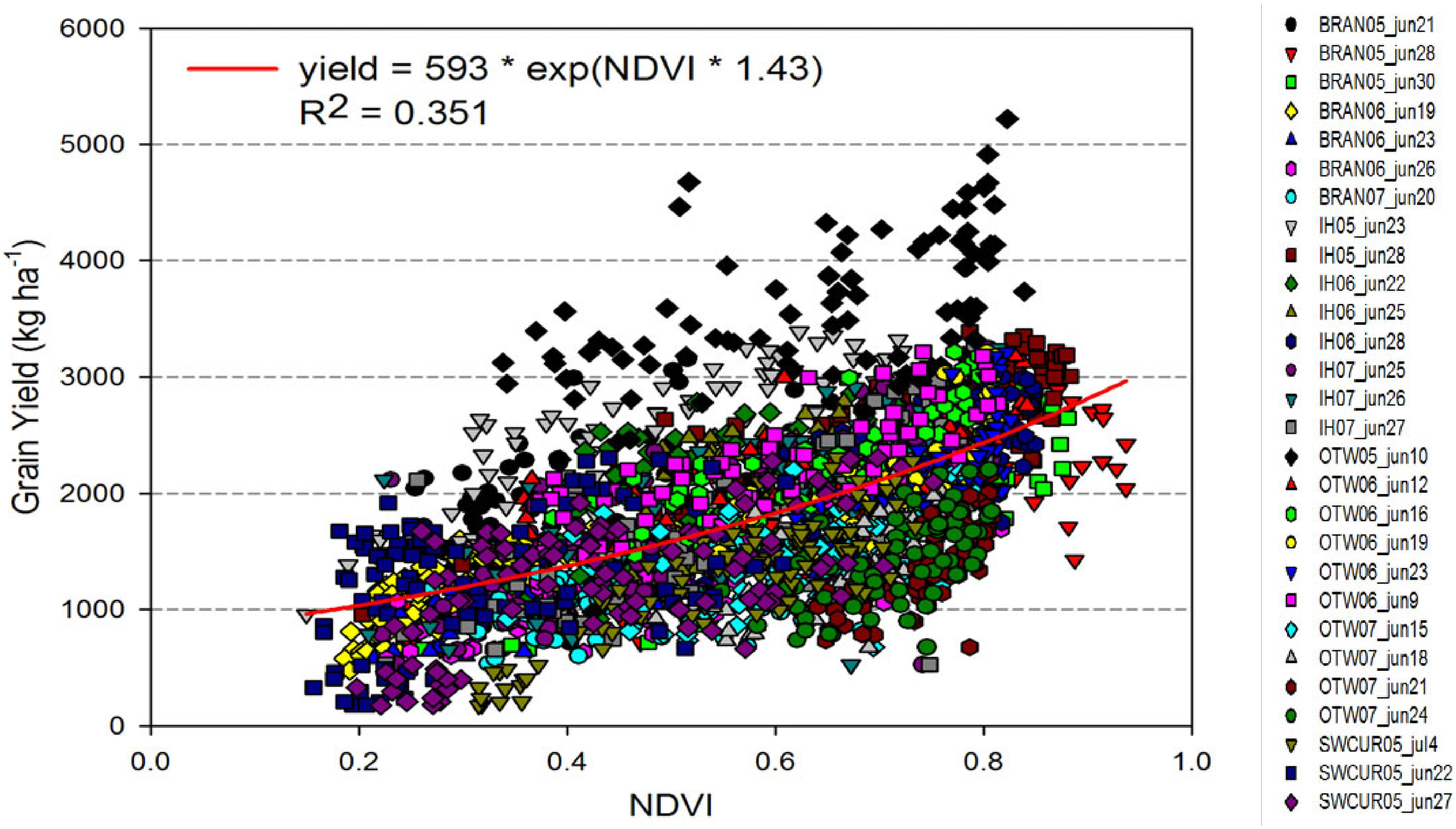

Figure A-19. Canola seed yield versus normalized difference vegetation index for all site-years (2005 – 2007) except for Scott in all three years and Swift Current in 2006 and 2007 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

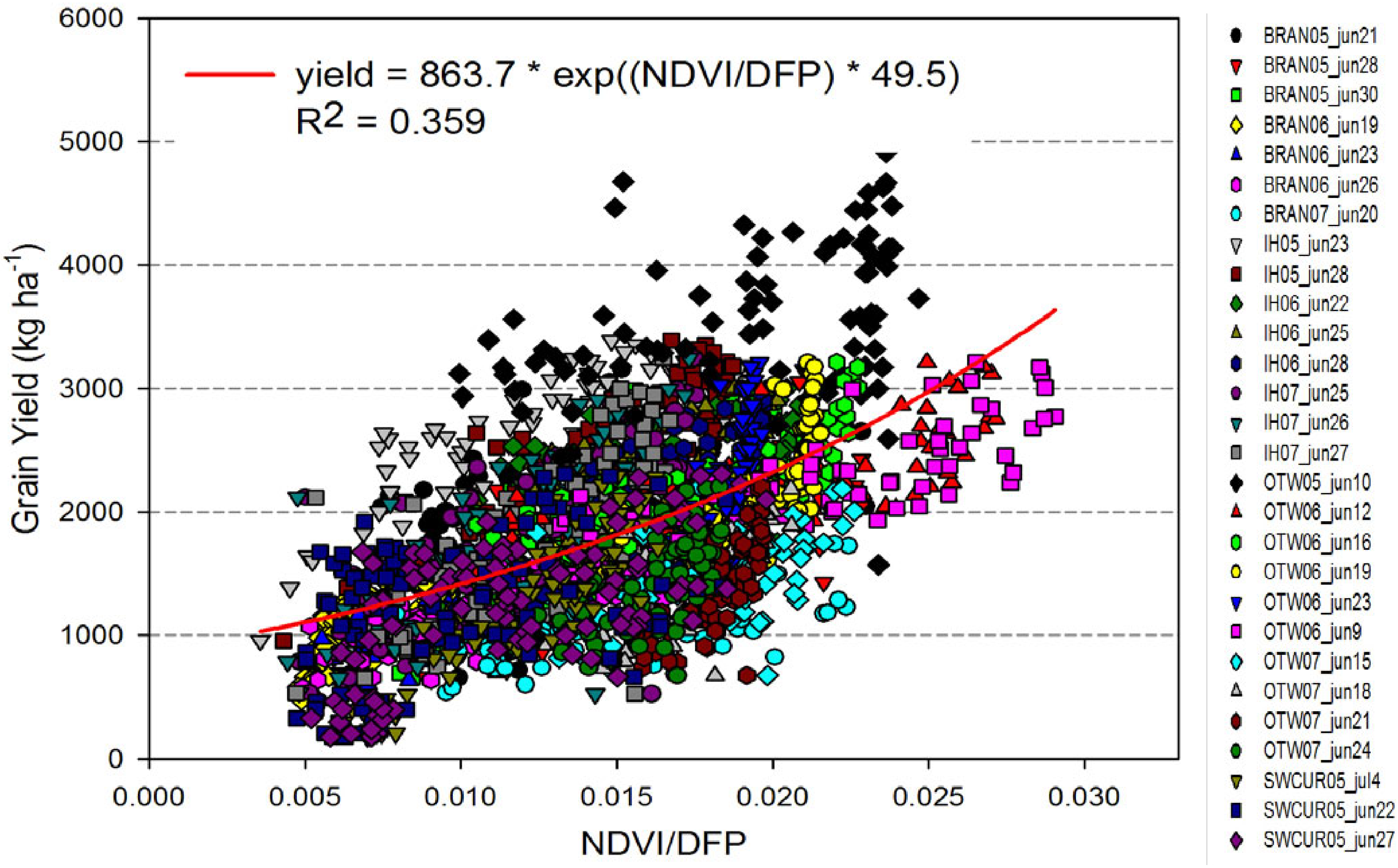

Figure A-20. Canola seed yield versus normalized difference vegetation index divided by days from planting (DFP) for all site-years (2005 – 2007) except for Scott in all three years and Swift Current in 2006 and 2007 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

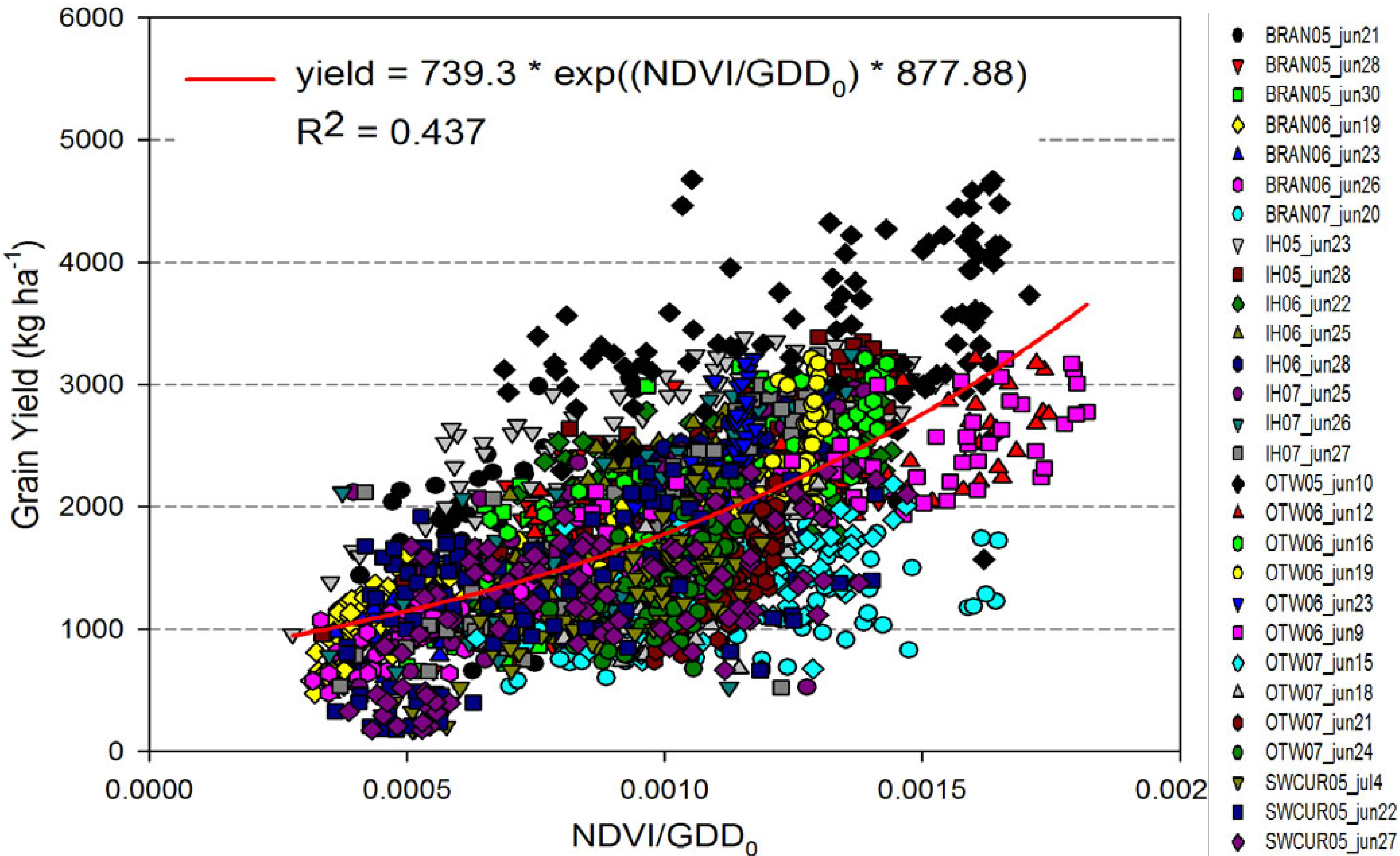

Figure A-21. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 0 ˚C) (GDD_0) for all site-years (2005 – 2007) except for Scott in all three years and Swift Current in 2006 and 2007 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

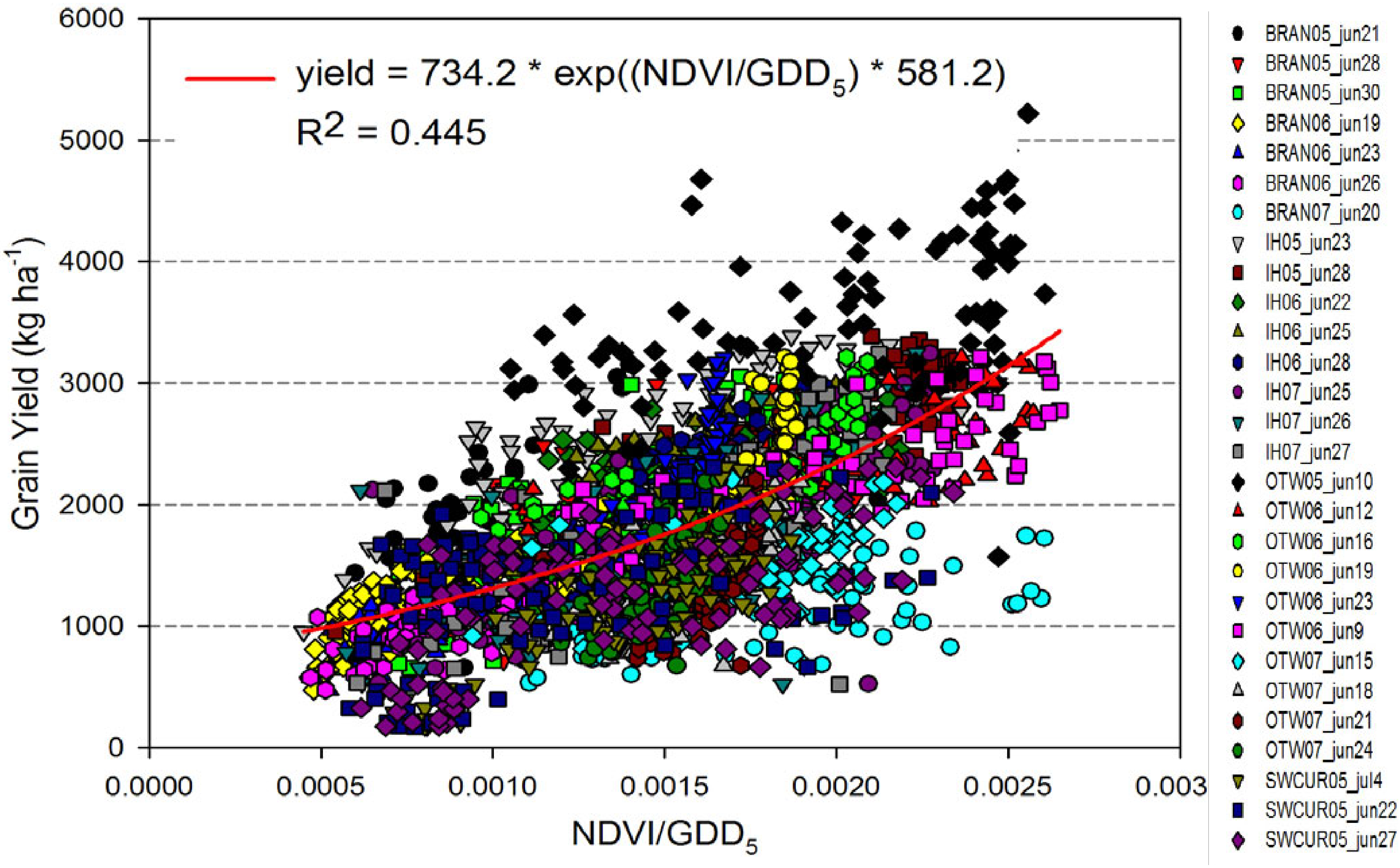

Figure A-22. Canola seed yield versus normalized difference vegetation index divided by growing degree days (base temperature 5 °C) (GDD_5) for all site-years (2005 – 2007) except for Scott in all three years and Swift Current in 2006 and 2007 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

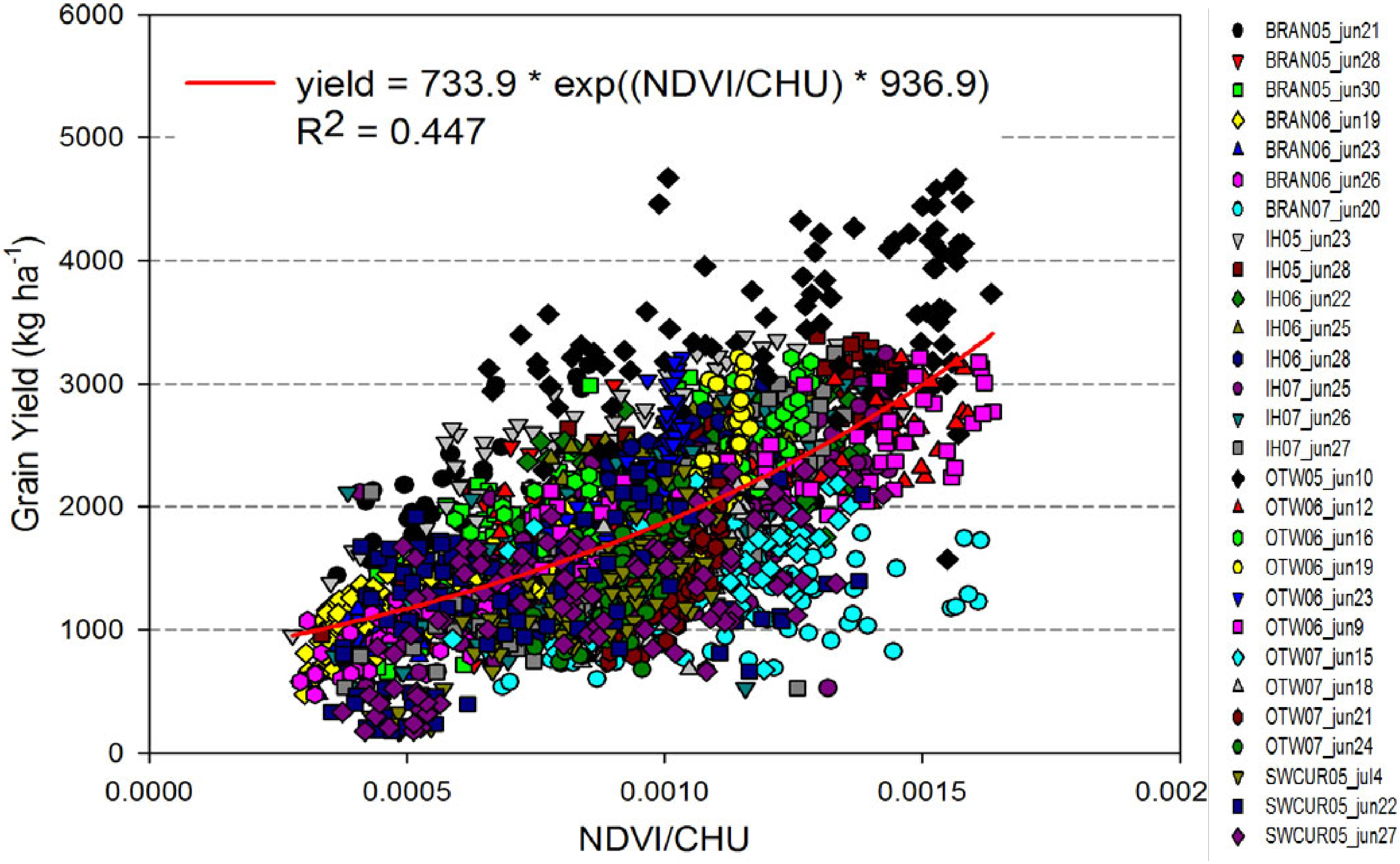

Figure 23. Canola seed yield versus normalized difference vegetation index divided by corn heat units (CHU) for all site-years (2005 – 2007) except for Scott in all three years and Swift Current in 2006 and 2007 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

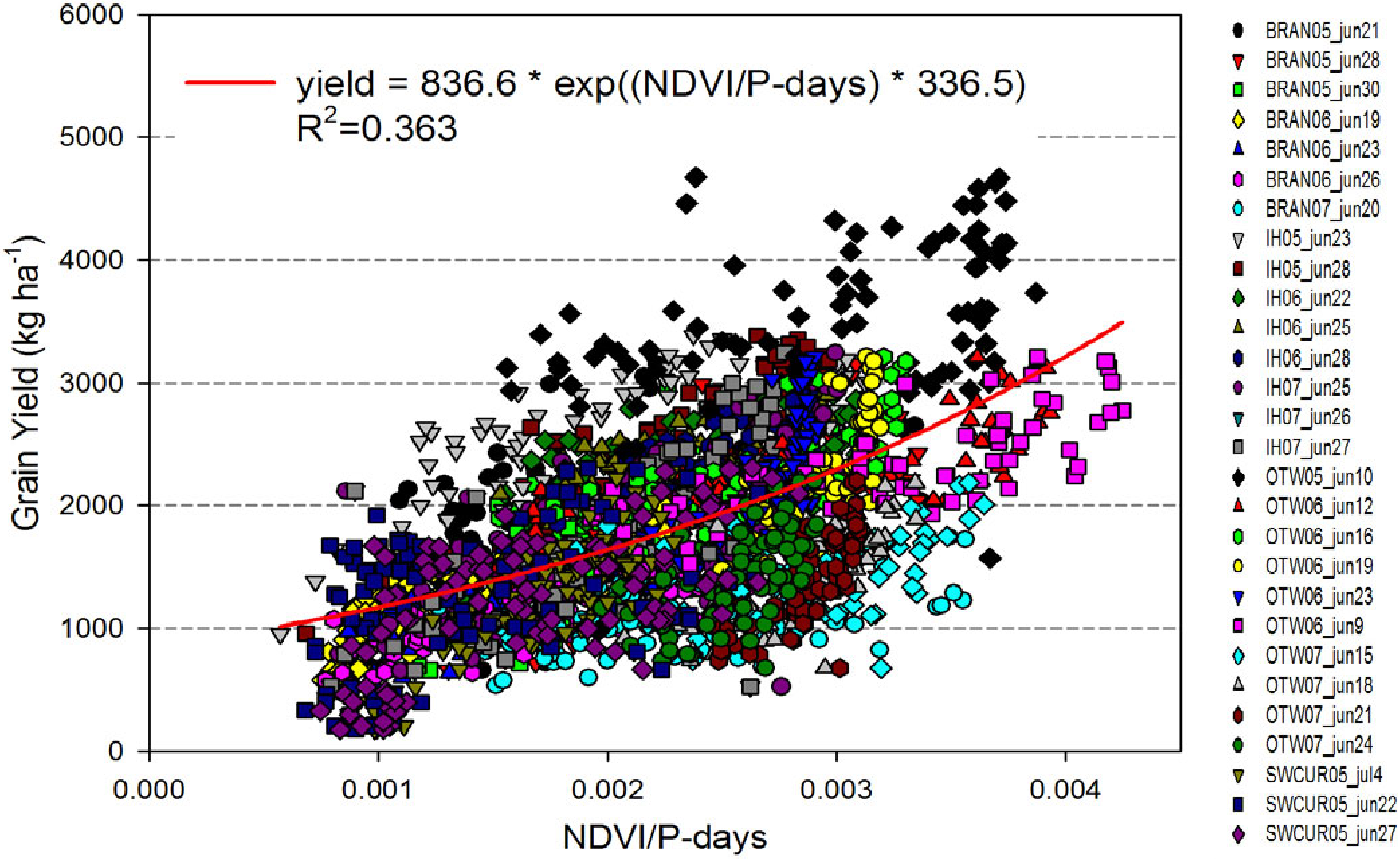

Figure 24. Canola seed yield versus normalized difference vegetation index divided by physiological days (P-days) for all site-years (2005 – 2007) except for Scott in all three years and Swift Current in 2006 and 2007 where NDVI was measured when the crop was between growth stages 2.5 and 4.2 (Harker and Berkenkamp 1975).

APPENDIX B – COMPARISON OF FINAL YIELD POTENTIAL EQUATIONS TO THOSE PROPOSED IN HOLZAPFEL (2007)

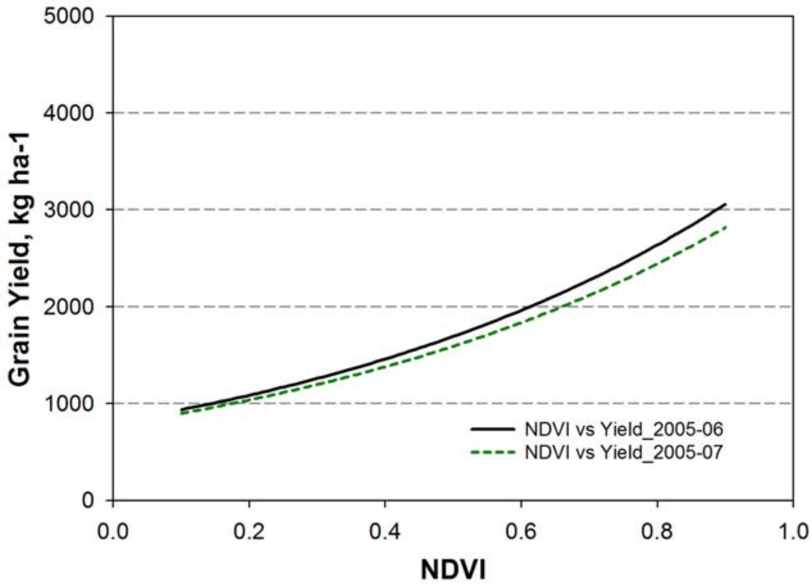

Figure B-25. Comparison of NDVI-canola yield equation proposed in Holzapfel (2007) versus that proposed when selected data from 2007 was included.

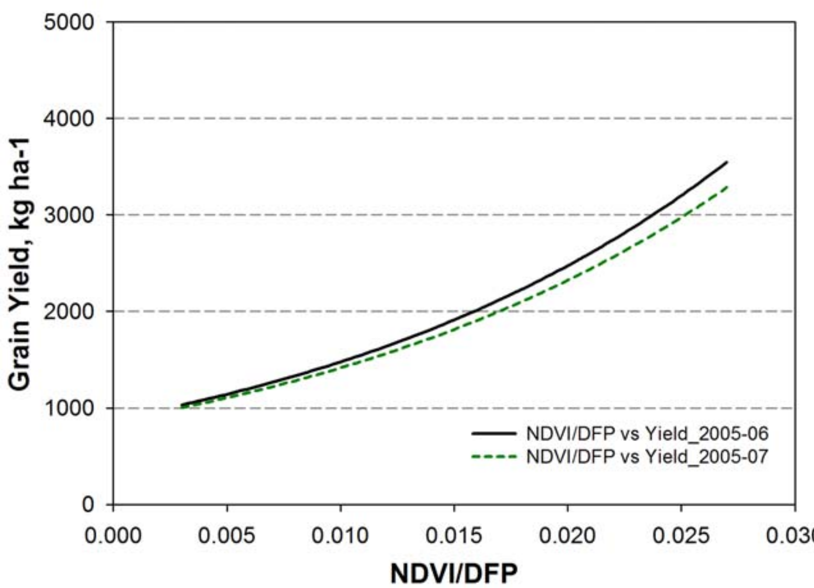

Figure B-26. Comparison of NDVI/DFP-canola yield equation proposed in Holzapfel (2007) versus that proposed when selected data from 2007 was included.

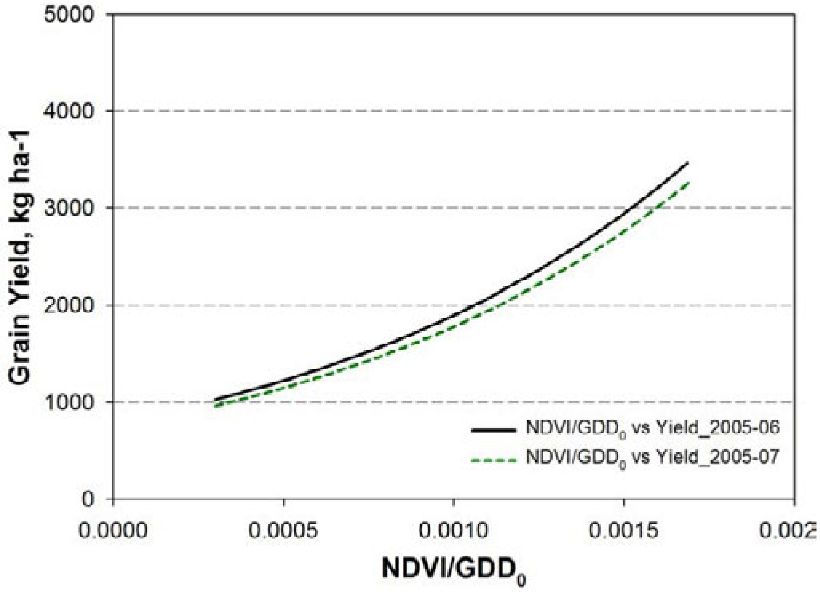

Figure B-27. Comparison of NDVI.GDD$_0$-canola yield equation proposed in Holzapfel (2007) versus that proposed when selected data from 2007 was included.

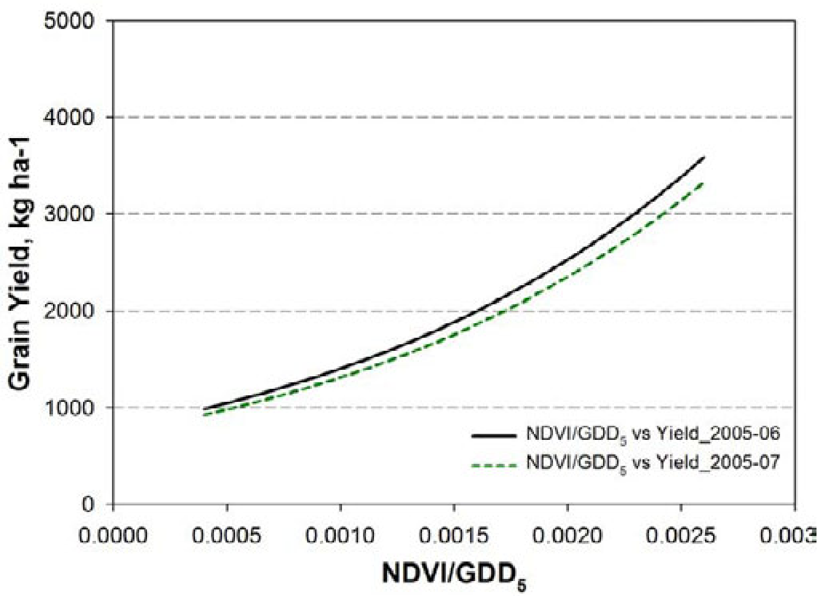

Figure B-28. Comparison of NDVI/GDD$_5$-canola yield equation proposed in Holzapfel (2007) versus that proposed when selected data from 2007 was included.

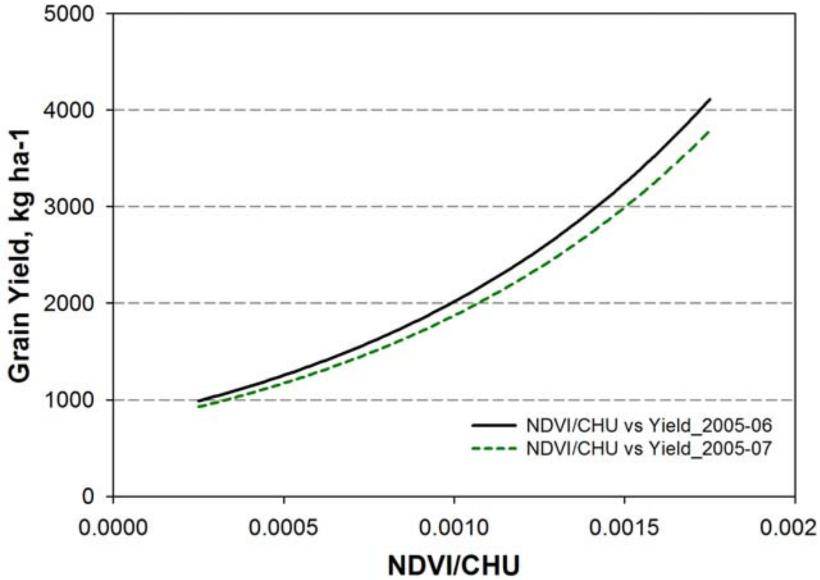

Figure B-29. Comparison of NDVI/CHU-canola yield equation proposed in Holzapfel (2007) versus that proposed when selected data from 2007 was included.

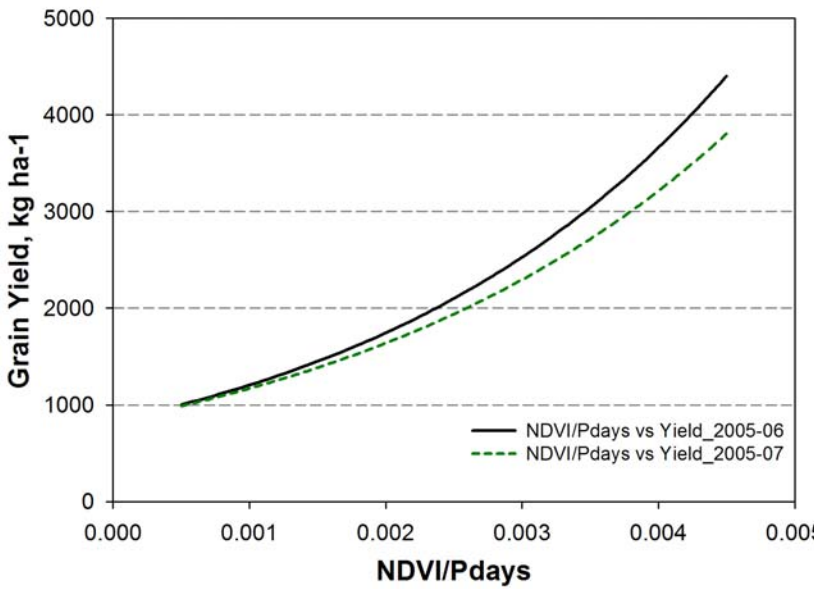

Figure A-30. Comparison of NDVI/Pdays-canola yield equation proposed in Holzapfel (2007) versus that proposed when selected data from 2007 was included.