Fertigation of Canola and Wheat

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Including also the final reporting for
Evaluation of sap nitrate for in-season assessment of crop nitrogen status
(Saskatchewan Canola Development Commission - AGR-14140)

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4. Abstract/Summary

Fertigation is the application of fertilizer in irrigation water. The practice is a well-established in intensive irrigated production operations and locally in field production of potatoes. More irrigated crop producers in the Canadian Prairies are obtaining the ability fertigate each year and are increasingly interested in fertigation as a potential means of increasing the efficiency of fertilizer N use by more closely matching the timing of nutrient application to crop needs.

The objectives of the *Fertigation of Canola and Wheat* project were:

a) To assess in-season application of N fertilizer to canola and wheat by fertigation (crop yield & quality, and GHG emissions),

b) To assess plant tests (tissue testing, plant reflectance) as in-season indicators of crop N needs, and develop test interpretive criteria, and
c) To transfer the related technology.

The project *Evaluation of sap nitrate for in-season assessment of crop nitrogen status* added on-site crop sap nitrate measurements to the suite of tissue testing technologies assessed.

Fertigation was assessed with irrigated canola and wheat field trials conducted in each of three years at the Canada-Saskatchewan Irrigation Diversification Centre ay Outlook. Treatments assessed the effectiveness of fertigation of N fertilizer as compared to N sidebanded with the seeding operation. Effectiveness of various plant testing technologies were also assessed as in-season guides for the need for additional N for the crops. Greenhouse gas emissions were monitored in selected treatments.

N fertilizer (urea-ammonium nitrate) applied through fertigation was found to be generally equivalent, on a pound-for-pound of N basis, to sidebanded urea with respect to their effects on crop yield and quality parameters measured for both crops. Up to 70 kg/ha of the total N was applied with fertigation operations that were conducted prior to heading of the wheat crop and flowering of the canola crop. Although wheat protein could be increased through fertigation, the effect was no greater than if the same amount of N was sidebanded.

Irrigators can use fertigation to postpone some of their N application to wheat and canola without loss of efficacy, increasing flexibility in their fertilizer management.

In-season crop tests evaluated to assess whether the crops actually need additional N fertilizer to be applied included measurements of total N and nitrate in the tissue and canopy reflectance (NDVI). The plant nitrate tests were found to hold the greatest promise for this purpose, at least for testing conducted at the canola bolting stage and wheat flag leaf stage. Plant sap nitrate tests can be conducted relatively quickly and easily on-farm.

Emissions of the greenhouse gas nitrous oxide were affected more by the total amount of fertilizer N applied than by which method was used to apply it. Relative emissions from the various N application method and timing treatments were not consistent from year to year.

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5. Extension Messages

- Nitrogen fertilizer applied through fertigation (i.e. in irrigation water) was equivalent to sidebanded N in terms of its effects on canola and wheat crop yield and quality including wheat protein. Treatments tested included total fertigation applications of up to 70 kg/ha of N made prior wheat heading and canola flowering. This means that producers with irrigation capacity have the flexibility to delay a portion of their N application to these crops without loss of fertilizer efficacy.

- Some in-season crop tests conducted at the canola bolting stage and the wheat flag leaf stage showed potential to assess whether the crops actually need additional N fertilizer to be applied. These included plant nitrate tests, some of which can be conducted relatively quickly and easily on-farm.

- Emissions of the greenhouse gas nitrous oxide were affected more by the total amount of fertilizer N applied than by which method was used to apply it. Relative emissions from the various N application method and timing treatments were not consistent from year to year.

6. Introduction

Fertigation is the application of fertilizer in irrigation water. It is a well-established practice in very intensive high-value irrigated production operations (greenhouses, and where drip irrigation is used), and in field production of potatoes. The capability to fertigate is being established on more and more irrigated fields in the Canadian Prairies each year. Irrigators are increasingly interested in fertigation as a potential means of increasing the efficiency of fertilizer N use by more closely matching the timing of nutrient application to crop needs. Fertigation avoids the added cost of enhanced efficiency fertilizer products which are often suggested to reduce losses of spring-applied N, and the extra field operation and crop damage associated with in-season fertilizer application. To achieve the very high and increasing yields of canola and wheat under irrigation, recommended N application rates are very high (e.g. >150 kg N/ha in SK).

The effectiveness of various fertilizer N management practices for field crops, including in some cases timing of application, has been the subject of many studies on the Prairies. However, the effectiveness of fertigation as a N application option for cereals and oilseeds has not been determined (aside from one study in Alberta). Adoption of fertigation has been limited, due in part to equipment suitability/capability at the farm level, but this is changing as producers adopt more sophisticated irrigation systems with fertigation capability. Potential exists for a large expansion in irrigated acres in the short term, particularly in Saskatchewan, potentially increasing the use of fertigation in field crops other than potato where it is extensively used currently. To-date, the large scale of field irrigation/fertigation systems has precluded fertigation at the traditional small plot scale (individual nozzles on field irrigation systems water areas larger than small plots, and fertilizer added to the water is applied through operating nozzles). As a result, very few studies which have evaluated in-season application of N fertilizers have employed true fertigation, since it is difficult to do at the small-plot level. Some studies, mostly with potato, have attempted to simulate fertigation at the small plot level, for example by applying the UAN form of fertilizer immediately followed by irrigation, or using a high-volume liquid fertilizer applicator. However, these approaches would not result in the same distribution of fertilizer N in the soil as would occur with actual fertigation.

Results will assist irrigated producers to select N management practices that minimize N rates and GHG emissions (and costs) without limiting crop yield and quality. If tissue N concentrations and/or NDVI readings are found to relate to the crop response to incremental N applied in-season, the interpretive criteria developed will provide producers with a means to assess in-season the sufficiency of N already applied to the crops. An overall reduction in N fertilizer use may result, as growers may routinely apply less N in the spring, knowing that they can check the status of their crop in-season to determine if additional N is required. This technology might also be applied to the much larger acreage of rain-fed

wheat and canola, especially in moister regions where mid-season top-dressing of N fertilizer is more consistently effective.

Results of GHG emissions assessments will inform industry and government of the merits of fertigation for mitigation of GHG emissions, providing information useful for developing recommendations and environmental programs.

7. Objectives

a) To assess in-season application of N fertilizer to canola and wheat by fertigation (crop yield & quality, and GHG emissions).
b) To assess plant tests (tissue testing, plant reflectance) as indicators of crop N needs, and develop test interpretive criteria.
c) Technology transfer, through field days, reports, publications, and meetings.

All objectives were successfully completed.

8. Methodology

i) *General*

The canola and wheat components of the project were conducted as two separate replicated small-plot trials adjacent to each other within the same field each year (except in 2019, when they were in separate fields but less than 100 m apart), on-site at CSIDC-Outlook (SW15-29-8-W3) in each of 2017, 2018, and 2019. Soil characteristics and test levels are presented (Table 1). All sites were on dominantly Bradwell Association soils that had been in irrigated annual crop production or trials for many years, though not used for research trials nor legume crop production for at least two years preceding the fertigation trials.

For each year the soil in each of the two planned trial areas was sampled to the 120-cm depth in the late fall of the year preceding the trial and tested for a wide range of parameters. For the 2018 and 2019 trials it was decided, based on assessment of the preceding fall testing results, that the trials needed to be moved to alternate locations due to unacceptably high and variable soil residual nitrate concentrations within the planned areas. Alternate suitable areas were identified and the soils were then sampled in the spring. Results for all areas actually used for the trials are tabulated (Table 1). All sites were non-saline at all sampled depths - data not presented.

The studies were each laid out using a split plot design with four complete blocks. Treatments in both studies were a factorial combination of five N rates sidebanded at seeding (0-35-70-105-140 kg N/ha as urea) as sub-plots, and four fertigation treatments as follows as main-plots:

A - Check - no fertigation
B - Fertigation @ 35 kg N/ha, at early application timing
C - Fertigation @ 35 kg N/ha, at late application timing
D - Fertigation @ 35 kg N/ha, at each of the early and late timings (for a total of 70 kg N/ha by fertigation)

The size and shape of individual sub-plots varied among the trials and years due differences in the linear irrigations systems in the fields used and in the suitable space available. Seeder row spacing was 10", and no additional gaps were left between the edges of plots. Sub-plots were eight 8 rows wide in 2017, and twelve rows wide in 2018 and 2019. Usable length of the plots were about 10, 8, and 9 m in 2017, 2018, and 2019 respectively. The end 2.5-3.0 m of planted area of each plot at both ends was not used for harvest or sampling because the overlapping patterns of the sprinkler nozzles applying the fertigation treatments necessitated a 5-6 m transition zone between fertigation treatments for accuracy of N application. The edge rows of the plots were not used for any sampling or harvest. Separate areas of the plots were also used for each plant sampling and for the final combine harvest.

The 2017 wheat study was seeded on canola stubble - the five others were seeded on wheat stubble. All were direct-seeded into the previous year's stubble without prior tillage. The canola studies were seeded to InVigor L252 canola at 6.9-8.4 kg/ha of seed, to target a plant population of 110 plants/m^2. The wheat studies were seeded to AC Carberry CWRS wheat at 111-126 kg/ha of seed, to target a plant population of 250 plants/m^2. Seeding depth was ~1.0 cm for canola and 2.0-2.5 cm for wheat.

Plots were seeded with single-disc research press drills. The side-banded N treatments were applied as granular urea (46-0-0) approximately 1.0" to one side of and 1.5" below the seedrows. No other fertilizer was placed in the sidebands. Details of other fertilizer applications are presented (Table 2).

Field operations on the plots and their timing are tabulated (Table 2). Applications of pest control products is not listed. Registered weed, disease, and insect control products were applied per label direction when required, resulting in generally effective control of the target pests (the few exceptions are noted in the Results and Discussion section).

Soil moisture tensions in all trials were monitored with WaterMark sensors at the 25 and 75 cm depths, or the 20 and 60 cm depths, in four or five locations in each trial. Irrigations were conducted to maintain soil moisture levels at or above optimum levels for crop growth. Rainfall (from the on-site Environment Canada weather station) and irrigation totals by month are tabulated (Table xx).

Plant counts were taken after plant emergence appeared to be completed in each trial. One (2017) or two (2018 and 2019) 1-m row sections were counted in each plot within the central six rows at locations determined prior to plant emergence (to avoid bias).

Fertigation treatments and other irrigations were applied with the linear irrigation systems present on all fields used for the trials. They used low-pressure Nelson sprayhead nozzles on drops, with convex or flat-trajectory fine-groove spray plates. They were set up to allow for at least 100% overlap of the nozzle spray patterns (for uniformity of application) while limiting the length of throw from each nozzle so that the unused areas at the end of each plot for treatment changes did not have to be even larger. Five or six consecutive drops/nozzles were used apply each fertigation treatment over the length of each plot. For fertigation, diluted 28-0-0 fertilizer (urea-ammonium nitrate solution) was injected into the irrigation line using an *Inject-O-Meter* piston pump (Figure 31). Field-scale irrigation and fertigation systems are not designed to facilitate plot-scale fertigation, so many measures were taken and protocols developed and followed to ensure that the fertigation treatments were accurately applied to each main-plot. Factors affecting N rate applied included actual output of the nozzles and fertigation pump under operating conditions, travel speed of the irrigation systems (including allowance for slippage), concentration of actual N in the fertilizer solution being injected, spacing of the nozzles, and number of nozzles operating (which determines total flow rate). The fact that the fertilizer solution injection point

had to be well upstream of the nozzles was also a complicating factor because it imposed a long delay in application of the fertilizer and did not allow for changes in the number of nozzles operating during a run. Most applications had to be done in the early morning since winds were usually high enough during the rest of the day to cause excessive drift of fertilizer solution between plots (Figure 32). Four different linear irrigation systems (differing in design and operation details) were used over the course of the study. Despite all these complicating factors that had to be considered, quantitatively accounted for, verified, and controlled, I am confident that the actual N application rates applied to the plots in the study were accurate within a few kg N/ha in each case.

Fertigation N applications were each made in irrigation events in which 0.5" of irrigation water was applied.; plots not receiving each fertigation were also irrigated within one day with 0.5" of water alone. Both crops were fertigated at the 5-6-leaf stage (*early* fertigation), and again at the bolting stage of canola prior to flowering or the flag leaf stage of wheat prior to heading (*late* fertigation).

Lodging was rated in each plot shortly before swathing (canola) or direct-harvesting (wheat).

The canola trials were swathed prior to harvest, while the wheat trials were direct-cut. A 1.524-m (6-row) wide plot combine was used for both. Final harvest areas in most plots were 11.0-13.5 m^2. Ends of the plots were trimmed well back before swathing (canola) or combining (wheat) to exclude crop adjacent to the alleyways or in the fertigation treatment transitions zones. No edge rows were included in the final harvest areas, nor rows adjacent to gaps (due to a missing seeded row for example), nor areas used for plant sampling, nor areas with growth clearly impacted by factors unrelated to treatment (e.g. seeding problem, poor emergence due to excess crop residue, or wildlife damage). The actual harvest area of each plot was determined prior to harvest. These protocols would prevent yield inflation due to plot edge effects.

They harvested samples were dried (when necessary), cleaned, and weighed, and average seed size (thousand kernel weight) and test weight (bulk density) were determined. A Foss Infratec™ 1241 Grain Analyser was used to determine seed moisture, protein (wheat only), and oil (canola only) contents. Canola green seed counts were determined using 300 seeds per plot.

ii) *Tissue sampling and analysis; NDVI readings*

Prior to each fertigation NDVI readings and tissue samples were taken from each plot in all studies. These were taken the day before fertigation except in the following cases:

2017 early: canola sampled the day of fertigation; wheat sampled two days prior to fertigation
2019 late: wheat sampled the day of fertigation

An averaged NDVI reading was taken from each plot by holding the trigger down on the GreenSeeker™ while walking down the length of the plot with the instrument held horizontally about one metre above the canopy. The centre 8 m or so of the plot length was used.

Tissue sampling was destructive to some of the plants, so the samples were taken from designated areas within each plot outside of the final harvest areas (at both ends of the plots in 2017, and from separate rows in 2018 and 2019).

Tissue sampling for wheat consisted of taking about 40 main stems from each plot (reduced to 30 for the later sampling date because the stems were larger) by snipping them off at ground level. In the lab, the youngest fully expanded leaves (YFEL) from the stems were removed (this would be the flag leaf for the later sampling), cut up into small (~1 cm) pieces, and oven-dried in small paper bags (for total N analysis). From the remaining portions of the plants, leaves attached to the bottom portion of the stem were stripped off (with their leaf sheaths) and discarded. The bottom ~5 cm portion of each stem was then cut off and used as the stem base sample (for nitrate analyses). Stem base samples were cut up with scissors into small pieces and mixed; a portion of each was oven-dried in small tins (for extractable nitrate analysis; fresh and dried weights were taken to determine gravimetric moisture content), and a portion was used for sap analysis. Sap was extracted using a special purpose hydraulic plant sap press.

Tissue sampling and sample processing for the canola was mostly similar to that described above for the wheat, with the following differences. The youngest fully expanded leaf (YFEL) with its petiole was removed from canola plants in each plot (rather than whole-stems; Figure 33). The leaf blades were cut from the petioles, and the blades were cut up and oven-dried for total N analysis. The remaining petioles were then processed as described above for the wheat stem bases. A simple hand-held plant sap press (cf. a garlic press) was used to extract the petiole sap (Figure 34) - the more succulent tissue of the canola petioles (in contrast with the wheat stem bases) did not require the extreme pressure of the hydraulic press to extract the sap.

The sap samples were analysed for nitrate content on-site at CSIDC by two separate methods:
1) LAQUAtwin compact nitrate meter (Horiba, Ltd.), which determine nitrate concentration using ion selective electrode technology.
2) Nitrachek nitrate meter (KPG Products Ltd.) with MQuant Nitrate Test strips (Merck & Co., Inc.). Nitrate in the sap reacts to form a red-violet dye in the pad of the test strip; the intensity of the color developed is read with the Nitrachek meter (a simple colorimeter reading light reflected from the strip).

Sap samples were diluted with distilled water as needed to bring concentrations within the range of the instruments. Most saps required dilution for the Nitrachek meter (to bring concentration below 113 ppm NO_3-N), while most did not require dilution for the LAQUAtwin meter (with a range up to 2200 ppm NO_3-N). Small disposable glass test tubes were used to hold the saps (as-expressed and diluted). Manual hand-held adjustable pipettes with disposable tips were used to dilute the saps as required.

All dried tissue samples were fine-ground and sent to AAFC-Summerland for total N (leaf blades) and extractable nitrate (stem base and petiole) analyses in Dr. Mehdi Sharifi's lab. Total N was determined with LECO CHN 628 analyzer. Nitrate in the stem base and petiole samples was extracted with water and determined by colorimetry with a segmented flow analyzer.

For each trial two or three selected plots of varying N treatment were also sampled at four or five additional dates to observe how the test levels change with time.

iii) *Greenhouse gas emission monitoring and fall residual soil N*

Nitrous oxide samples were collected following protocols similar to those described by Rochette et al. (2004). Briefly, acrylic frames (25 cm × 25 cm × 15 cm) were inserted into the soil to a depth of 5 cm and were placed to include one crop row with its sideband. The frames were kept in place throughout the growing season. To ensure a similar plant density around the frame as in the rest of the plot, canola was

hand seeded along the outside of the side of the chamber nearest the row originally seeded within the chamber. If necessary, these seed rows were thinned after crop emergence to match the plant density of the balance of the plot. Lids were sealed to the frames for the sample collection period, and gas samples were drawn from the chamber headspace after a 30-minute period by fully filling disposable 20 mL polypropylene syringes and transferring to pre-evacuated 13 mL glass Exetainer™ tubes for transport to the laboratory. Gas sampling was generally done weekly, but with increased frequency when expected emission activity was high (after irrigation or rainfall events, and fertigation of N).

The concentration of N_2O in the Exetainer™ tubes was determined using a gas chromatograph equipped with a 63Ni electron capture detector. The minimum detectable concentration difference, calculated as the mean difference plus twice the standard deviation of a series of ambient air samples (Yates et al. 2006), for the system averaged <10 ppbv. Nitrous oxide flux rates were calculated as the change in concentration over time (subtracting the time zero concentration from the final concentration), with adjustments for nonstandard conditions of humidity, temperature, and barometric pressure. Time zero values were estimated using a method similar to that described by Anthony et al. (1995). Seasonal estimates of N_2O emissions were calculated by interpolating between data points and integrating over time assuming a constant flux (Lemke et al. 1999).

Nitrous oxide yield intensity values were calculated by dividing grams N_2O-N ha^{-1} by kg seed yield ha^{-1}. These intensity values are calculated using direct N_2O emissions and cumulative emissions from the growing season (not including spring thaw) only.

Soil samples in each plot were obtained by taking three cores (3.8 cm i.d.) from the 0–15, 15–30, 30–60, 60–90 and 90–120 cm depths after harvest each year. After removing visible roots and residues, the soil samples were air-dried and ground to pass through a 2 mm sieve for laboratory analyses. Nitrate (NO_3-N) and ammonium (NH_4-N) in the soil were extracted using a 1:5 soil : 2 mol L^{-1} KCl solution (Maynard et al. 2008), and the concentration was determined with a Technicon Autoanalyzer II (Technicon Industrial Systems 1973).

iv) *Statistical analysis*

Conventional analysis of variance procedures are not alone appropriate for assessment of all results of the study as a split-plot design because the two variables (fertigation treatment and banded N rate) are both N application rates (so in a sense confounded). A more ideal treatment schedule for analysis would have included main plots based on the total amount of N applied and subplots for the fertigation treatments (thus maximizing sensitivity to detect fertigation effects). However, that would not have been practicable because the fertigation treatments must be separated by wide areas due to the throw distance and overlapping patterns of the sprinkler nozzles through which the treatments are applied. Therefore the data is presented in ways that don't always correspond to the treatment design to allow comparisons of fertigation effects at equal total applied N levels. Use of data from only selected treatments also permits valid statistical assessment for the limited range of total applied N treatments included (so long as all total N rates included exist for all fertigation treatments included). Graphical and other methods of presenting and evaluating results were used as appropriate for the various datasets produced by the project.

For yield and quality parameters, results were statistically analysed by analysis of variance in three ways (for each of the two crops):

- for all 20 treatment combinations as discrete treatments in a RCBD. This disregards the split plot aspect of the design, but allows all treatments to be included in one analysis.
- for all four fertigation treatments as main plots, and only the treatment combinations which have total N applications (sideband + fertigation) of 70, 105, and 140 kg N/ha as subplots (i.e. a 4x3 factorial).
- for the None, Early, and Late fertigation treatments only, as main plots, and only the treatment combinations which have total N applications (sideband + fertigation) of 35, 70, 105, and 140 kg N/ha as subplots (i.e. a 3x4 factorial). This was included to capture significant differences at the 35 kg/ha total N level, which is not included in the Both fertigation treatment.

Treatment effects were considered significant if they met the selected criterion ($P<0.05$) by any of the above three analyses. The results of the statistical analyses are not tabulated here, but were used to select which parameters to present means for graphically and discuss. Results are presented graphically in a format which shows the mean in relation to total N applied for each fertigation treatments.

9. Results and Discussion

i) Canola stand, yield, and quality

Plant stand density was determined before any fertigation treatments were applied, so was analysed statistically only for the effects of banded N rate. Canola stand density averaged 80, 60, and 119 plants/m^2 in 2017, 2018, and 2019 respectively (data not presented). Density was well below the 110 plants/m^2 target in two of the years. However, the Canola Council of Canada states that for yield potential "the critical level for plant populations is somewhere between 40 and 50 plants per square metre" (https://www.canolacouncil.org/canola-encyclopedia/plant-establishment/evaluating-the-stand/). The lowest mean count for any treatment in any year was 56 plants/m^2. There were no significant effects of banded N rate on stand in any year, though regression analysis suggested a weak trend toward lower counts with increasing N ($P=0.096$) in 2018 only. Considering these points, and the fact that stands tended to be fairly uniform without gaps, is likely that separation of the seedrow from the sideband was adequate to avoid effects on yield due to toxicity of the banded N, and that yields were affected little if at all by low stand densities.

Canola yield response to N application was moderate in 2017 and 2018, and strong in 2019. Without added N, yield was reduced by N deficiency by about 30% in 2017, 20% in 2018, 62% in 2019, and a mean of ~35% over all three years (Figure 1). Response to N was likely limited by subsoil residual nitrate (Table1). Yields were strongly related to total N applied (sidebanded + fertigated) up to about the 105 kg/ha N level in 2017, the 70 kg/ha level in 2018, and the 140 kg/ha level in 2019. However, yields differed significantly among fertigation treatments ($P=0.028$) only in 2018, and only for the for the 70-140 kg/ha total applied N range. The pattern of differences is inconsistent however, with the non-fertigated treatment not yielding consistently higher or lower than those receiving fertigation. The interaction effects of fertigation treatment and total N applied was also significant for that year only, for both the 70-140 kg/ha N range ($P=0.013$) and the 35-140 kg/ha N range ($P=0.007$). Yields were strongly related to total N applied ($P<0.001$) by at least two of the three statistical measures in each of the three years, and by all three measures for the three-year means. Clearly N applied through fertigation had a similar overall effect on yield as that sidebanded at planting on a pound-for-pound basis.

The local N fertilizer recommendation for irrigated canola would be about 200 kg/ha of N for the general soil residual nitrate levels (0-12" depth) and yield levels that occurred in these studies (2020 Irrigation Crop Diversification Corporation *Irrigation Economics and Agronomics*). As clear yield response in each year occurred only to much lower applied N levels, the recommendations may be too high and/or residual nitrate present below 12" should be determined and considered in the calculation of N fertilizer needs.

Canola seed oil content declined very significantly and consistently with total N applied in 2017 and 2019, and in the thee-year analysis (Figure 2). There was also a weak trend to reduced oil content with increasing total applied N in 2018 if the treatment receiving no N is excluded. The three-year average decline in oil content was about 1% per 50 kg/ha of total applied N through the 50-200 kg/ha N range. This is important to the industry because the oil is the most valuable component of the canola, though current farmgate prices are not adjusted for seed oil content. Many studies have shown canola oil content to decline and protein content (not determined in this study) to increase with increasing applied N rates. Fertigated N had the same effect on wheat protein as sidebanded N in this study.

Canola test weight increased very slightly but significantly with total N applied in 2017 and 2019, but not in 2018 nor in the three-year analysis (data not presented). Small effects of treatments on seed size (TKW) were also found in 2018 and 2019, mostly related to total N applied (data not presented). However, seed size varied greatly among the years of the study - averaging 3.5 mg in 2017, 5.9 mg in 2018, and 3.7 mg in 2019. Despite the average seed size being 67% larger in 2018 than in 2017, yields and mean oil contents were similar between those two years; the reason for the difference is not known.

Canola green seed count was very low in all years - well under 0.5% in every treatment every year (only two seeds were green out of 24,000 crushed in 2019!). Green seed counts were unrelated to treatments in 2018, and weakly but inconsistently related in 2017.

Lodging of the canola crop was minor in all years of the study, with no treatment averaging higher than 3.0 on the 1-9 rating scale in any year (data not presented). Lodging rating was unrelated to treatment in 2019, but clearly increased with total N applied ($P<0.01$) in 2018 and 2019 - fertigation treatment had no effect in any year.

ii) Wheat stand, yield, and quality

Plant stand density was determined before any fertigation treatments were applied, so was analysed statistically only for the effects of banded N rate. Wheat stand density averaged 184, 139, and 169 plants/m^2 in 2017, 2018, and 2019 respectively (data not presented). These densities were well below the 250 plants/m^2 target, though all stands appeared uniform with no bare patches. Undercounting of the plants may have been a factor. ANOVA indicated a just-significant effect of banded N rate on stand ($P=0.041$) in 2017 only - it is not regarded as meaningful because there was no trend to increasing or decreasing stand with increasing N rate; the regression of stand on N rate was not significant ($P=0.52$) and the 0 and 140 Kg/ha banded N rates had the same stand densities. Although yield potential may have been slightly limited by low stand density, separation of the seedrow from the sideband was clearly adequate to avoid toxicity of the banded N at higher rates used.

Wheat yields in plots apparently not limited by N deficiency averaged approximately 6300, 5700, and 4700 kg/ha (94, 85, and 70 bu/ac) in 2017, 2018, and 2019 respectively. Only the 2017 yield would be considered a *good* yield for irrigated CWRS wheat in Saskatchewan. Yields in 2018 were probably limited primarily by late seeding date (due to the need to relocate the trial from the planned area) and leaf diseases (despite fungicide application). The low 2019 yield was primarily due to Take-all root rot which appeared serious over the whole study area.

Wheat yield response to N application also occurred in all years of the study. Without added N, yield was reduced by N deficiency by about 55% in 2017, 45% in 2018, 25% in 2019, and a mean of ~45% over all three years (Figure 3). Response to N was likely limited by subsoil residual nitrate (Table 1). Yields were strongly related to total N applied (sidebanded + fertigated) up to about the 175 kg/ha N level in 2017, the 125 kg/ha level in 2018, and the 80 kg/ha level in 2019. Yields differed significantly among fertigation treatments ($P<0.01$) only in 2019, and only for the 70+ kg/ha total applied N range where the non-fertigated treatment yielded lower than all fertigated treatments - this will be discussed below.

Grain protein content increased significantly ($P<0.01$) and consistently with total applied N rates of 70+ kg/ha N in all years (Figure 4). Grain protein frequently does not increase (and sometimes even decreases) with low rates of applied N because growth/yield increases can be so large as to dilute the applied N in the much increased yield.

Wheat grain protein was significantly affected by fertigation treatment only in 2019, when the non-fertigated treatment produced grain consistently very high in protein (14.7-15.1%) at all N rates - even including the 0 banded N rate which received no N at any time (Figure 4). Grain protein from the non-fertigated treatment was higher in protein than that from all fertigated treatments at all total N levels below 140 kg/ha N. This is very unusual, since N applied later always increase protein at least as much as N applied at seeding so long as it is available to the crop. All fertigated treatments showed the typical increases in protein with rate of total applied N. This was also the year when non-fertigated treatment had significantly lower yields than the fertigated treatments through the 70-140 kg/ha total applied N rate range. None of the obvious arguments about relative availability of sidebanded vs. fertigated N explain both the yield and protein results obtained. The high grain protein in the non-fertigated treatments suggest that N was abundant - yet yields were lower than in all fertigated treatments. I can suggest two factors that may be involved:

a) The non-fertigated main plots in two of the blocks were at the ends of the study, where growing conditions may have been poorer. Those two main-plots produced generally lower yields (at equivalent total applied N rates) than all other main-plots. Generally lighter growth was also noted in-season in the main-plot that had the lowest yield. The need to assign fertigation treatments to the small number of main-plots results in poorer apparent fertigation treatment performance if growing conditions are poorer in even one or two of the main-plots with that treatment.
b) The fertigation applications may have had some positive effect on crop growth unrelated to crop N nutrition. The 2019 study was severely affected by Take-all root rot (*Gaeumannomyces graminis*), which probably reduced yields by 25% or more. The disease appeared to affect the whole study area quite uniformly. Is it possible that application of the UAN solution had some inhibitory affect on the disease organism directly, or helped the plants resist effects of the disease by some mechanism other than simply improved N nutrition? The generally highest yields in the *Both* fertigation treatment (though not likely statistically significantly higher than in the other fertigated treatments) would be consistent with this explanation. Other agronomists and a plant pathologist I consulted with on the subject were not aware of any such an effect.

If the poorer yield of the non-fertigated treatment was due to N deficiency stress the yield should still have increased with increasing total applied N rate - which it did not. For these various reasons I suggest that the poorer performance of that treatment in 2019 is not due to the relative availability of the fertigated vs. sidebanded N, so should not be regarded as significant in the overall interpretation of the study results.

Studies that include treatments with N applied at various times during the growing season often find that grain protein levels are stimulated more by N applied later than by N applied at planting. That was not observed in this study. The likely explanation is that the N applied in all treatments (even the later fertigation) was available to the crop early enough to allow for the maximum yield obtainable with the total amount of N that was applied - so N was not being introduced to the crop too late for it to be useful in increasing yield.

Wheat grain test weight showed a trend to increase with total N applied in 2018 (P=0.06) and in the three-year analysis (P=0.09). Differences among treatments were small (<2 kg/hl in 2018). Average grain size increased significantly with total N applied in 2017 and 2019, and in the three-year analysis (P=0.001 or lower). In 2019 yield was not related to grain size, suggesting that the poorer yield of the non-fertigated treatments were not due to poor conditions for filling late in the season.

Although lodging induced by fertilization with N can be a problem in irrigated wheat, there were no effects of treatment on lodging in any year of this study. In 2018 all wheat plots were lodged flat by a snowfall on Sept. 21-22 (~15 cm of heavy, wet snow). Improved weather, manual separation of the harvest rows before combining (Figure 36), and drying of the harvested samples allowed for a successful harvest without substantial harvest losses or sample deterioration. In 2017 and 2019 (and prior to the September snowfall in 2018) there was no substantial lodging in any treatments of the wheat studies. AC Carberry is a semi-dwarf cultivar that has quite good lodging resistance.

By and large the agronomic results of this study agree with those of a similar study conducted in Alberta with wheat and canola (Pauly 2017). They also found that the effectiveness of fertigated N at the growth stages used in this study was equal to that applied in sidebands.

iii) Tissue sampling and analysis; NDVI readings

<u>Dry matter content of petiole and stem base samples</u>

Nitrate is measured in the dried petiole/stem tissue as well as in sap from the fresh petioles and stems in this study. The dry matter percentage of the petiole/stem tissue is required to compare and convert between the two approaches to testing. If they are measuring the same nitrate in the tissue is should be possible to convert diagnostic criteria (e.g. critical nutrient levels) developed with one approach for use with the other.

Mean dry matter contents of the petiole/stem tissue at the two primary sampling stages used are presented (Table 3). Wheat stem base tissue was much higher in dry matter than canola petioles - much of the reason it is much more difficult to express sap from the former. The dry matter content of the petioles and stems increased greatly between the two sampling times. Dry matter content of the tissues from the most N-deficient treatments of both crops were up to about 30% higher in dry matter content than those from the treatments well-supplied with N - i.e. the samples from the N-stressed plants were

less succulent. Those differences are not presented, since when samples are taken in practice one would not know what the N sufficiency status is in advance.

Measures of crop N status over the sampling season

Tissue samples and NDVI readings were taken from all plots just prior to each fertigation event. A few plots of each crop were also sampled prior to the first fertigation, between the fertigation events, and two or three times after the late fertigation to show patterns in the measurements over time. Sampling frequency was approximately weekly, with the second and fourth samplings corresponding to the early and late fertigation times. The patterns in the results over time tended to be similar across years - results are presented for 2018 only as an example (Figure 5).

Results of all measurements generally showed very consistent patterns with N treatment and crop stage. This indicates that the sampling, processing, and testing protocols were rigorous (e.g. a large number of plants in each plot were sampled) and carefully conducted by all involved.

NDVI readings increased rapidly to about the time of the late fertigation for canola and for a week or so longer for the wheat (Figure 5 (a)). This was clearly due more to increasing canopy cover than N status of the plants (though there were differences among treatments as well - likely due much more to affects of the N on development of canopy cover than to color of the plants themselves). For wheat, there were substantial differences in NDVI among treatments by the time of the late fertigation, but not at the early fertigation time. For canola in 2018 there were larger differences among treatments at both fertigation times. Canola NDVI dropped off sharply during the two weeks following the late fertigation - this was clearly due to flowering, as they rose again later as flowering ended. Although the effects of canola flowering would be a serious complication in interpretation of NDVI for canola from the start of flowering, the focus of this study was at earlier stages only. The effect of canopy cover is complicating for both crops until full cover is present, since canopy cover is affected by many factors other than sufficiency of N.

Canola sap and dry tissue extractable nitrate concentrations tended to drop sharply between the two fertigations, as did the wheat sap and extractable concentrations in the unfertilized treatment (Figure 5 (b-d)). Concentrations varied widely with treatment. It is challenging to use concentrations that change rapidly with growth stage/time as indicators of nutrient sufficiency because interpretive criteria must also then change rapidly with growth stage. However, it is helpful for concentrations to vary widely with plant N sufficiency status (e.g. with treatments in this study) because that reduces the need for high accuracy in the testing protocol and in the criteria adjustments for growth stage.

The two sap nitrate tests used the same extracted sap, varying only in the method of nitrate detection in the sap. Results appear generally very similar between the two procedures, though nitrate measurements using the ion selective electrode instrument were quite consistently somewhat higher than those using the colorimetric procedure (Figure 5 (b, c)). This was most obvious for the saps relatively low in nitrate concentration. Comparison of results from the sap nitrate procedures with those from the dry tissue nitrate extraction procedure (expressing all on the dry tissue weight basis) a showed good correlation among methods, but the nitrate concentrations measured by the ISE procedure were quite consistently higher than those measured by the other tests. This suggests a positive interference for the ISE measurements. Both sap procedures can quite easily be conducted on-site, and even in-field, with relatively simple and inexpensive (~$1000) instruments, with some training.

Leaf blade total N concentrations also changed substantially with time between the two fertigations for both crops, though proportionately much less than sap nitrate concentrations(Figure 5 (e)). Differences between treatments were also proportionately much less for total N. Need for analytical accuracy is greater for total N because the concentrations vary much less between sufficient and moderately deficient samples. Total N is also not generally adaptable to on-site, and especially in-field, testing due to the time, facilities, and instrumentation required - it is always conducted at laboratories.

Suitability of the tests for diagnosis of crop N sufficiency

It is clear that the N treatments strongly influenced all the tissue test measurement results, and NDVI though to a lesser extent (Figure 6). Statistical analysis of those effects could fill volumes, but would be of little application because fertilization is not conducted merely to raise tissue nutrient concentrations, but rather to improve crop yield and quality, which was already statistically assessed. The various measures of nutrient status used in this study were included primarily to assess their suitability for diagnosing situations where the crop is deficient in N for optimum yield and therefore likely to respond to additional N applied by fertigation.

A relative seed yield for each plot was estimated. For each experimental block (consisting of 20 plots) a (100%) reference yield which estimated as the yield of the third highest measured yield from the block. In each study at least three of the highest-N treatments appeared to produce yields clearly unaffected by N deficiency. The third-highest yield was selected over the highest to avoid use of a possible outlier yield value (or one with a very high positive error component) as a reference. Seed yield of each plot in the block was then expressed as a percentage of the reference yield. Test levels from each plot (by all methods used) were then related to the individual plot relative yields to assess if the test is truly reflecting yield-limiting N deficiency, and if so - what test level is critical for separating N-deficient from sufficient test levels.

For plots that were fertigated the N applied by fertigation (conducted *after* the tissue testing) would have reduced or eliminated yield loss due to any N deficiency that had been present in the crop. Yield results described above indicated that N applied by fertigation at either or both times was generally equal to sidebanded N for meeting crop N requirements for maximum yield. So for plots receiving fertigation, the yield used was not that from the plot itself, but rather from the sub-plot within the same main-plot that was to have the same total amount of N applied (including all fertigations) as the plot itself had at the time of tissue sampling. The main-plots were compact, so all plots within each were assumed to have similar potential yield and soil N availability.

For each N assessment method the relationships between test level and relative yield are presented in Figures 7-26, for each crop and each sampling time (*Early* and *Late*). Different colored markers are used for each year. It is important that critical levels for nutrient tests be relatively stable across years and growing conditions (within the reasonably expected local limits for those conditions). For each year a suggested critical test level is indicated (with a cross in the color of that year's markers), separating the generally N-sufficient plots from those generally having suboptimal yield, except where there appeared to be no relationship between test level and relative yield. This generally follows the original Cate-Nelson procedure (Cate and Nelson, 1965). Those critical levels are tabulated by crop, sampling time, test, and year (Table 4). A general critical level for each test and sampling time is also suggested, and the overall reliability of the test and critical level is rated. The procedure was subjective to allow for weighting of the individual trials differently in estimation of the best overall critical level (less importance was attributed to trials with poorer or variable yields, low N response, or other growth

problems). It should be noted that the relationships between test level and relative yields are graphed for each small plot (rather than for treatment means, as often indicated in other studies) - this results in much wider spread of the graphed data points, but also allows for outliers to be disregarded rather than having them affect the mean values.

In case the yield adjustment described above for the fertigated plots was not valid, relative yields from those plots are given a different marker style that those for the non-fertigated plots. In general however, both datasets from within each study appeared to indicate similar relationships between test level and relative yield. The lowest yields are always from the non-fertigated plots because only that fertigation treatment had a true 0-N check.

The NDVI readings were largely unrelated to likelihood of crop response at the early sampling time (5-6 leaf stage) for either crop (Figures 7 and 17). This is not surprising, as the readings appeared to be reflecting canopy cover only, which in a field would be affected by many factors other than N status of the crop. The relationships between NDVI and crop N status were slightly better at the later sampling stage for both crops, but still poor and critical levels were not very consistent from year to year.

Sap testing at the earlier sampling time was a moderately poor indicator of crop N status for canola, and a very poor indicator for wheat (Figures 9 and 11, and 19 and 21). Sap nitrate provided a markedly better index at the later sampling stage for both crops (Figures 10 and 12, and 20 and 22), but especially for the wheat - the relationship shown in Figure 20 provides a good basis for the use of the test and the critical level as determined in this study at the flag leaf stage of wheat.

The test using nitrate extracted from dried petioles or stem bases also was a poor indicator of additional N needs at the earlier sampling time, but improved by the late sampling time (Figures x and xx), though the consistency in critical levels among years was somewhat poor.

The total N content of the leaf blade at the early sampling time was also related poorly (canola) to not at all (wheat) with likelihood of plant N response (Figures 15 and 25). By the late sampling time it was still a poor a poor index for canola due to inconsistency across years (Figure 16), but was fair for wheat (Figure 26).

In general, the sap nitrate tests showed to have some promise as indicators of plant N status (and hence need for application of additional N through fertigation) when conducted at the bolting stage of canola and flag leaf stage of wheat, but not at the 5-6 leaf stage of either crop. In these studies the relationships between the plant test values and relative yield were not as close as hoped for in most cases. The soil residual N at depth (below 60 cm; Table 1) in most of the trial locations may have been a factor. The crops may have accessed that N after the tissue testing was conducted but still soon enough to use it to enhance yield.

<u>Some general comments about the tests conducted for use on the farm</u>

The NDVI test does not measure N specifically, so a high-N reference strip in each field would be needed to relate the readings specifically to N status of the crop. Even then, full canopy cover would likely be needed to prevent the readings from being much more an index of canopy cover than of crop N status.

Sampling in the field: It is very easy to sample the canola petioles at all stages. The wheat stem bases are a little more work (to snip at ground level and cut off the bottom ~2" of main-stem), but also not very difficult or laborious.

Sample processing: samples of (~20-30) petioles and stem bases are both easy to cut up with a scissor.

Sap expression: Extracting sap from the canola petioles with simple hand tools (e.g. heavy-duty garlic press) requires some effort but is quite simple and quick to do. Expressing sap from the wheat stem bases is much more difficult because it requires much more pressure to get sap from the stem bases which have lower moisture content. The hydraulic sap expresser was effective, but somewhat expensive (~$800), and probably not practicable for in-field use due to the more laborious cleaning required between samples. A simpler hand-operated device that develops sufficient pressures may be possible to develop.

Nitrate determination in the sap: Both methods can be quite easily learned, but there are number of steps, including calibrations with one or more standard solutions for each test. Simple inexpensive lab items are required - tissues, small tubes or vials for sap samples, distilled water bottle for cleaning. The protocols are definitely more suitable for use indoors than in-field, though could be done in a vehicle if supplies are kept handy. Sap dilution with distilled water is required for most saps for the colorimetric test, but only for the very high-nitrate saps for the ISE method. A simple dilution protocol using inexpensive and mostly disposable lab items could be set up. Drift of the concentration reading on the ISE device was problematic for many of the sap samples. The single value readout on the colorimetric device was better in that respect. However, repeated measurements were not very reproducible with either instrument (manufacturer suggestions of ±10% precision for both may be optimistic at times). This is in part why differences in nitrate concentrations between sufficient and deficient plants must be substantial for these tests. In general, I felt I had more confidence in the concentrations measured with the colorimetric procedure, and preferred to use it despite the additional dilution usually needed. The two meters each cost ~$800. The colorimetric device requires a consumable test strip for each reading and some for calibrations - about a dollar each. However the electrode on the ISE device should be replaced periodically (perhaps annually?) - ~$300. Both devices come set up to display concentrations as nitrate, but can be set to read out in units of nitrate-N if desired.

iv) Greenhouse gas emission monitoring and fall residual soil N

Nitrous oxide emissions during the 2017 growing season were generally low. Mean daily values ranged from an occasional small negative flux (uptake) to a maximum positive flux of 180 µg m^{-2} d^{-1} (Figure 27). While the magnitude of emissions appeared to be influenced by the different N-fertilizer management strategies, the temporal distribution of fluxes did not appear to be strongly influenced. As an example, Figure 27 presents the mean daily N_2O emissions for the check (no N applied) and three of the N-management strategies (140 kg N banded at seeding, or 105 kg N banded at seeding and a further 35 kg N applied in either an early or a late fertigation event). Emissions were low immediately after the first N application at seeding (May 16), but increased markedly during the period between May 23 and June 6. Emissions were slightly elevated on the "Banded" and the "Banded + Early Fertigation" immediately after the early fertigation application which occurred on June 15, but no detectable increase in emissions occurred following the late fertigation event (June 30).

Estimated cumulative N_2O losses during the 2017 growing season ranged from 150 to 470 g N ha^{-1} (Table 5). Cumulative losses were lowest from the two treatments receiving no N at seeding (check and the early and late fertigation totalling 70 kg N ha^{-1}) and highest from the treatments receiving 140 kg N ha^{-1}, with the latter treatments being significantly different from the no N treatment, but not significantly different from treatments receiving 70 kg of fertilizer-N ha^{-1}. However, the treatment receiving both an early and a late fertigation application was the exception to this pattern. Losses were not significantly higher than the no N treatment - even at the 140 kg N rate. Treatments receiving a total of 70 kg of fertilizer-N ha^{-1} did not have cumulative losses that were significantly different from the no N treatment. A simple correlation comparison revealed that average cumulative N_2O losses were positively and significantly correlated with total N applied (R = 0.66), and that this association was considerably stronger (R = 0.85) when comparing cumulative losses with the amount of N applied at seeding. Estimated cumulative N_2O losses during the spring thaw period were low, ranging between about 70 and 130 g N2O-N ha^{-1}, with no significant treatment differences. Thus, treatment differences in the total annual loss estimates (growing season plus the following spring thaw period) essentially mapped with the differences observed during the growing season.

Nitrate measured in the soil profile after harvest of the canola crop tended to be modest, suggesting reasonably efficient uptake of the applied fertilizer. Statistical analysis of the total nitrate in the 0-120 cm depth indicates that nitrate values tended to be higher under treatments receiving both an early and a late fertigation application (Table 6). This is most notable on this treatment when N applied totalled to 210 kg ha^{-1}. This treatment showed total soil nitrate in the profile that was significantly higher than all other treatments.

Closer inspection of the data shows that much of the before-mentioned treatment differences are driven by higher nitrate levels in the top two increments (i.e. 0-30 cm depth; Figure 28). This implies that current year fertilizer-N is the most likely source of the accumulated nitrate. Nitrate values in the deeper depths tended to be slightly higher on this treatment but the differences were generally not significant (data not shown). Elevated soil nitrate in the surface horizon would also imply a greater risk of high N_2O emissions during the subsequent spring thaw period. However, this potential was not realized as no treatment differences were noted during the 2018 snow melt period (Table 5).

Nitrous oxide emissions during the 2018 growing season were generally low. While the magnitude of emissions appeared to be influenced by the different N-fertilizer management strategies, the temporal distribution of fluxes was not strongly influenced. As an example, Figure 29 presents the mean daily N_2O emissions for four treatments receiving a total of 70 kg N. For treatment “A3” all N was banded at seeding (i.e. 70 + 0 + 0), while treatment “B2” and “C2” received 35 kg N at seeding followed by a further 35 kg N at the early (June 27) or late (July 10) fertigation events, respectively. The “D1” treatment received no N at seeding followed by 35 kg N at both the early and the late fertigation events (i.e. 0 + 35 + 35). Emissions increased markedly on all treatments during the period between May 29 and June 22, but most particularly for the “A3” treatment which received 70 kg fertilizer N at seeding. Small increases in daily emissions were noted following each fertigation event. Treatments receiving N applications at this time had slightly higher emissions compared to the “A3” treatment (N only at seeding), but the magnitude of the difference was minimal.

Estimated cumulative N_2O losses during the 2018 growing season ranged from 110 to 690 g N ha^{-1} (Table 7). Cumulative losses were lowest from the no N applied treatment and highest from the treatment receiving both an early and late fertigation, with the latter treatments being significantly different from the no N and the 70 kg N at seeding (banded), but not significantly different from other treatments

receiving fertilizer N. Apart from N_2O loss tending to be higher on treatments receiving N compared to the check, no relationship with rate or application time was observed. A simple correlation comparison revealed that average cumulative N_2O losses were positively and significantly correlated with total N applied (R = 0.68), but the association with N applied at seeding was less strong than in 2017, but still positive and significant (R = 0.58).

Estimated cumulative N_2O loss during the 2019 spring thaw period was extremely low, ranging between about 30 and 80 g N_2O-N ha^{-1}, with no significant treatment differences. Thus, treatment differences in the total annual loss estimates (growing season plus the following spring thaw period) essentially mapped with the differences observed during the growing season.

Nitrate measured in the soil profile after harvest of the canola crop in 2018 tended to be higher than in 2017. Statistical analysis of the total nitrate in the 0-120 cm depth indicates that nitrate values tended to be higher under treatments receiving a total of 140 kg N ha^{-1} (Table 8). There was no consistent trend evident in soil nitrate levels associated with timing of fertilizer N applications. Significantly higher levels of nitrate observed on treatments receiving 140 kg N ha^{-1} was apparent for all soil layers except the 90-120 cm depth. Increased levels of nitrate in the deeper layers of the soil profile suggests a higher risk for nitrate leaching in these treatments. Despite receiving a total of 140 kg N ha^{-1}, treatment "C4" (Banded + late fertigation) was an exception to the aforementioned trends. This treatment had soil nitrate levels throughout the soil profile that were not significantly different than the treatment "A1" (0N applied) (Figure 30).

Nitrous oxide emissions during the 2019 growing season were moderate (daily flux data not shown). The magnitude of emissions were influenced by the different N-fertilizer management strategies, but the temporal distribution of fluxes were not. Highest emissions activity occurred from shortly after seeding (May 14) until just prior to the first fertigation event (June 18). Although emissions remained elevated on all treatments that received N fertilizer compared to the check, emissions were not noticeably increased by the early and/or late (July 3) fertigation events.

Estimated cumulative N_2O losses during the 2019 growing season ranged from 360 to 800 g N ha^{-1} (Table 9). Cumulative N_2O loss response pattern on the N-management treatments was very similar to those observed during the 2017 and 2018 growing season in that cumulative losses were lowest from the no N applied treatment and were generally highest from the treatments receiving total N application of 140 kg N ha^{-1}. The exception being the treatment "D3" (70 + 35 + 35 = 140 kg N ha^{-1}) which had losses that were comparable to treatments receiving 70 kg N ha^{-1}. A simple correlation comparison revealed that average cumulative N_2O losses were positively and significantly correlated with total N applied (R = 0.72), and that this relationship was considerably stronger (R = 0.84) when comparing cumulative losses with the amount of N applied at seeding.

When considering mean cumulative N_2O loss across the three growing seasons (Table 10), a couple of interesting trends can be observed, although only a few of the differences were shown to be statistically significant. In general, fertilizer N application did increase N_2O emissions. That is to say, treatment "A1" (0N applied) had the lowest emissions, although the difference was not significant compared to treatments "A3" (banded = 70 kg N ha^{-1}), "C2" (banded + late fertigation = 70 kg N ha^{-1}) and "C4" (banded + late fertigation = 140 kg N ha^{-1}). Of note, both treatments receiving a late fertigation treatment ("C2" and "C4") had emissions that were not significantly different from the 0N treatment ("A1"). This is of particular interest because other treatments receiving a total of 140 kg N ha^{-1} tended to have the highest emissions - although the difference was not significant for most when compared to

treatments receiving 70 kg N ha^{-1}. Further, in 2018 these two treatments appeared to have the lowest leaching risk of the treatments receiving fertilizer N.

In 2017 and 2018 treatments receiving an application of fertilizer-N tended have higher N_2O yield-intensities (calculated using direct N_2O emissions only) than the check (0N) treatment (data not shown). Treatments receiving applications of 140 kg of N tended to have significantly higher intensities compared the check, but differences were generally not significant compared to the treatments receiving 70 kg of N. In turn, N_2O yield-intensities on treatments receiving 70 kg of N tended to be not significantly difference than the check treatment. The 2019 growing season was an exception in this regard. The intensity of the check treatment was significantly higher than all other treatments, with no significant differences between treatments receiving fertilizer-N. Closer inspection of the data revealed that the higher N_2O yield-intensity on the check treatment was driven by the very poor and highly variable yields measured on this treatment.

Trends observed when comparing the three-year cumulative N_2O yield-intensities (cumulative yield divided by cumulative growing season N_2O) were generally consistent with the 2017 and 2018 crop years. Intensities tended to be lowest on the check treatment (i.e. fertilizer-N increased N_2O yield-intensities), but the differences were only significant compared to treatments receiving 140 kg N ha^{-1} (Table 11). Treatment " C4" (Banded + Late Fertigation = 140 kg N) was an exception, having an intensity value not significantly different than the check. The N_2O yield-intensities of treatments receiving 70 kg of fertilizer-N tended not to be significantly different from either the check or treatments receiving 140 kg of fertilizer-N. Treatment "B2" (Banded + Early Fertigation = 70 kg N) was an exception, having an intensity value significantly higher than the check treatment.

10. Conclusions and Recommendations

The effectiveness of N fertilizer application by fertigation (i.e. in irrigation water) to canola and wheat was evaluated over three years of field research trials at the Canada-Saskatchewan Irrigation Diversification Centre at Outlook. Applications of 35 kg/ha of fertilizer N were made by fertigation at one or both of two crop stages - the 5-6-leaf stage of each crop, and the bolting (canola) or flag leaf (wheat) stage. This was done in combination with a range of rates of sidebanded N also applied. Results indicated that the N applied through fertigation was generally equally effective to sidebanded N (pound for pound) in terms of its influence on crop yield and quality. Specifically, wheat protein was increased, and canola oil content was reduced, with increasing amounts of total N applied. It did not matter if a portion of that N was applied through fertigation as described above. Since sidebanding N is a very effective means of supplying N, it is valuable to know that application of up to 70 kg/ha of the fertilizer N can be delayed and applied through fertigation without loss of fertilizer efficacy. On the other hand, delaying a portion of the N application in that way did not provide any incremental benefit in terms of yield or quality. Soil and weather conditions were not conducive to in-season loss of applied N through leaching.

Delaying application of a portion of the fertilizer N to the crop by use of fertigation allows for in-season assessment of the crop status to determine if the additional N is needed. Several methods of crop N testing were assessed for this purpose. Certain methods involving measurement of nitrate in the plant tissue were found to be more effective than measurement of crop NDVI or of total N content of the plant leaves. Preliminary interpretive criteria for the tests were suggested, including for sap nitrate tests

which can be conducted fully on-farm. Tests take for the earlier fertigation application timing were less effective than those at the later timing for diagnosing crop N status.

Greenhouse gas emissions were monitored in selected treatments of the canola studies only. Total seasonal emissions of nitrous oxide (N_2O) were well under one kg N_2O-N ha^{-1} in all monitored treatments in all years. Emissions generally increased with N application rate, though the influence of sidebanding vs. fertigation were inconsistent.

11. Is there a need to conduct follow up research?

Further similar work focussed on efficacy of fertigation of wheat and canola is not needed, as both this study and the earlier similar Alberta study were in agreement.

Additional work should be undertaken to further develop the tissue tests and refine interpretive criteria (especially for the sap tests which can be done on-farm with increasingly effective yet inexpensive technology). Effective and rapid in-season assessment of crop N status may allow for producers to reduce overall N use, which could lead to reduced costs and greenhouse gas emissions.

12. Patents/ IP generated/ commercialized products: none

13. Technology transfer activities

In 2017 the Fertigation Study was featured prominently in the morning tours of the CSIDC Annual Field Day held on July 13 (~180 attendees participated in those tours). It was also featured in two other tours open to the public on August 15 - the ICDC Tour (att. 35) and CSIDC Evening Tour (att. 30). The PI spoke about the Fertigation Study and the Sap projects in all three cases. The PI also showed the study to many individuals and small informal groups who visited CSIDC over the growing season. Its location close to the CSIDC yardsite made it very accessible. A description of the Sap Nitrate project was also included (with a photo) in Canola Digest - Science Edition 2017.

Some results from the Fertigation Project were included in a presentation about canola N needs and GHG emissions by the PI to the Great Plains Soil Fertility Workshop in March 2018 in Denver.

In 2018 the Fertigation Study was again featured prominently in the morning tours of the CSIDC Annual Field Day held on July 12; the PI shared the tour stop with Errin Willenborg (SaskCanola), who spoke about clubroot of canola. The sap nitrate analysis procedure was also featured in one of the afternoon tours that day. The PI delivered an invited presentation on the fertigation project to the 23rd Annual Irrigation Saskatchewan Conference in Moose Jaw in December.

The PI attended the American Society of Agronomy Annual Meetings in San Antonio, Texas, in November 2019. He delivered an oral presentation on the fertigation and sap nitrate projects to that conference. The PI delivered an invited presentation primarily on the fertigation and sap projects to the 24rd Annual Irrigation Saskatchewan Conference in Moose Jaw in December 2019.

14. Industry contributions or support received. None.

Note however that the SCDC-funded project reported herein (*Evaluation of sap nitrate for in-season assessment of crop nitrogen status*) is a fully industry-funded enhancement to the larger ADF-funded fertigation project.

15. Acknowledgements

The *Fertigation of Canola and Wheat* project was a collaborative venture; the partial funding for it contributed by Saskatchewan Ministry of Agriculture and the Canada-Saskatchewan Growing Forward 2 bi lateral agreement (through the Agriculture Development Fund) is acknowledged and greatly appreciated.

The funding for the *Evaluation of sap nitrate for in-season assessment of crop nitrogen status* project provided by the Saskatchewan Canola Development Commission is also acknowledged and greatly appreciated.

Both funding sources were acknowledged in all presentations at above-mentioned tours and events. Funding from ADF and SCDC was also acknowledged by signage at the study sites when they were included in planned tour events.

Mr. Don David (AAFC-CSIDC) was the lead technician. His and our summer students and casual staff did excellent work on the project each year.

As collaborators, Evan Derdall advised regarding the fertigation system design and use, and Drs. Denise Neilsen and Mehdi Sharifi managed the laboratory determinations of tissue total N and extractable nitrate. Dr. Reynald Lemke managed all greenhouse gas-related activities under the project and drafted all reporting on that subject as well as on the post-harvest residual soil nitrate levels.

Appreciation is also extended to Mr. Doon Pauly of Alberta Agriculture and Forestry for ongoing advice and consultation on the project.

16. Appendices

Appendix i. Tables

Table 1. Soil characteristics and test levels for all fertigation trials.

Analysis*	Soil Depth (cm)	Unit	2017		2018		2019	
			Canola	Wheat	Canola	Wheat	Canola	Wheat
Sampling date:			10 November 2016		- 30 May 2018 -		03 May 2019	04 October 2018
Organic mat.	0-15	%	2.4	2.2	1.9	1.9	2.4	2.1
Carbonates	0-15	%$CaCO_3$-eq.	2.1	4.1	1.8	1.7	0.9	2.3
pH	0-15		7.9	8.0	8.1	8.1	8.1	8.2
Nitrate	0-15	kg/ha	10	8	9	10	6	8
(as NO_3-N)	15-30	kg/ha	12	7	6	7	5	18
	30-60	kg/ha	26	18	20	12	20	40
	60-90	kg/ha	34	22	24	12	42	46
	90-120	kg/ha	40	40	46	26	56	42
	0-60	kg/ha	48	33	35	29	31	66
	60-120	kg/ha	74	62	70	38	99	88
Ammonium	0-15	ppm	4	3	6	3	5	6
(as NH_4-N)	15-30	ppm	4	2	5	3	4	6
	30-60	ppm	4	3	6	4	4	6
	60-90	ppm	4	5	4	3	3	6
	90-120	ppm	5	5	5	3	3	6
P	0-15	ppm	19	29	12	15	11	6
K	0-15	ppm	200	234	165	174	151	174
Sulphate	0-15	kg/ha	22	High	52	28	22	44
(as SO_4-S)	0-60	kg/ha	High	High	High	High	High	High
Zn	0-15	ppm	0.7	0.8	0.7	0.8	0.8	0.5
Fe	0-15	ppm	11	9	8	9	18	10
Mn	0-15	ppm	2.7	1.6	4.1	2.8	5.6	3.6
Cu	0-15	ppm	0.56	0.60	0.36	0.41	1.6	0.45
B	0-15	ppm	1.1	1.1	0.6	0.5	0.6	0.8
Particle Size	0-15	%S-Si-C	32-52-16	35-48-17	65-30-5	63-32-5	53-37-10	51-42-7
Texture			SiL	L	SL	SL	SL	SL

* Methods: OM - total C by combustion less IC, x 1.72; Carbonates - manometric; pH - in 1:1 soil:water suspension; Nitrate and Sulphate - 0.01M KCl extract; Ammonium - 2M KCL extract; P - Olsen method; K - NH_4OAc extract; all micronutrients in DTPA-sorbitol extract; Particle Size Analysis - hydrometer.

Table 2. Blanket fertilizer applications and dates of operations in all fertigation trials.

	2017		2018		2019	
	Canola	Wheat	Canola	Wheat	Canola	Wheat
Dates of operations						
Planting	May 16	May 16	May 29	May 29	May 14	May 15
Swathing	August 24	-	Sept. 7	-	August 30	-
Combining	Sept. 7	August 30	Sept. 26	October 5	Sept. 16	Sept. 18-19
Blanket fertilizer applications*						
Placement:	- - - seedrow - - -		- - - - - - - - - - pre-plant band - - - - - - - - - -			
Rates (kg/ha actual nutrient)						
P_2O_5	15	15	50	50	25	50
K_2O	-	-	50	50	15	15
S	-	-	10	10	-	-
Cu	-	-	5	5	-	4

* Pre-plant bands were applied deeper than seeding depth, perpendicular to seeding direction, within a day prior to seeding, with a drill with 7.5" (2018) or 10" (2019) opener spacing. Fertilizer sources used were triple superphosphate (0-45-0), potash (0-0-60), potassium sulphate, and copper sulphate/oxide (2018) or copper sulphate (2019).

Table 3. Mean dry matter contents of canola petiole and wheat stem base samples.

Crop	Mean dry matter content of samples			
Sampling time	2017	2018	2019	2017-2019 Mean
		%		
Canola				
Early	6.1	7.8	7.9	7.2
Late	9.2	10.0	8.3	9.2
Wheat				
Early	11.6	12.3	14.0	12.6
Late	16.6	15.9	18.3	16.9

Table 4. Critical levels and ratings for plant tests.

Crop, sampling time and test	Units	2017	2018	2019	Overall	Reliability
Canola						
Early						
NDVI	index	-	-	0.50	0.50	Very poor
Sap-ISE	ppm NO_3-N	1930	1850	1870	1900	Fair
Sap-Col.	ppm NO_3-N	n.d.	1700	1010	1350	Poor
Extraction	% NO_3-N	2.49	1.45	1.50	1.50	Fair
Total N	% N	6.85	6.46	5.76	6.0	Poor
Late						
NDVI	index	0.80	74	76	77	Poor
Sap-ISE	ppm NO_3-N	1050	180	640	800	Fair
Sap-Col.	ppm NO_3-N	n.d.	61	630	600	Fair
Extraction	% NO_3-N	0.78	0.03	0.62	0.70	Fair
Total N	% N	6.90	4.05	4.30	5.61	Poor
Wheat						
Early						
NDVI	index	-	0.30	-	-	None
Sap-ISE	ppm NO_3-N	1860	1200		1500	Poor
Sap-Col.	ppm NO_3-N		750	320	700	Poor
Extraction	% NO_3-N	0.79	0.75	0.26	0.78	Poor
Total N	% N	5.94	5.90	-	5.90	Poor
Late						
NDVI	index	0.72	0.67	0.52	0.70	Poor
Sap-ISE	ppm NO_3-N	1220	1120	1360	1230	Good
Sap-Col.	ppm NO_3-N	-	1080	740	1000	Fair
Extraction	% NO_3-N	0.66	0.76	0.37	0.69	Fair
Total N	% N	4.90	5.10	5.00	5.00	Fair

n.d. - not determined (this test was not conducted in 2017)

Table 5. Estimated cumulative N_2O loss from various fertilizer-N application strategies at Outlook, SK. during the 2017/2018 annual cycle.

N-Management	Total N Applied	Growing Season 2017	Spring Thaw 2018	Combined
	kg N ha^{-1}	g N_2O-N ha^{-1}		
A1 - (Check)	0	200 c	90	290 c
A3 - (Banded)	70	260 bc	130	380 abc
A5 - (Banded)	140	400 ab	100	500 ab
B2 - (Banded + Early Fertigation)	70	250 bc	130	380 abc
B4 – (Banded + Early Fertigation)	140	470 a	80	550 a
C2 – (Banded + Late Fertigation)	70	250 bc	70	330 bc
C4 – (Banded + Late Fertigation)	140	340 ab	110	460 ab
D1 – (Early + Late Fertigation)	70	150 c	70	220 c
D3 - (Banded+Early + Late Fertig.)	140	210 bc	120	340 abc

Table 6. Nitrate measured in the soil profile under various fertilizer-N application strategies at Outlook, SK. after harvest of the 2017 crop year.

N-Management	Total N Applied	Soil Nitrate (0-120 cm)
	kg N ha^{-1}	
A1 - (Check)	0	32 c
A3 - (Banded)	70	48 c
A5 - (Banded)	140	52 bc
B2 - (Banded + Early Fertigation)	70	31 c
B4 – (Banded + Early Fertigation)	140	36 c
C2 – (Banded + Late Fertigation)	70	56 bc
C4 – (Banded + Late Fertigation)	140	53 bc
D1 – (Early + Late Fertigation)	70	94 b
D3 – (Banded + Early + Late Fertigation)	140	91 b
D5 – (Banded + Early + Late Fertigation)	210	130 a

Table 7. Estimated cumulative N_2O loss from various fertilizer-N application strategies at Outlook, SK. during the 2018/2019 annual cycle.

N-Management	Total N Applied	Growing Season	Spring Thaw	Combined
	kg N ha^{-1}	g N_2O-N ha^{-1}		
A1 - (Check)	0	100 c	40	140 c
A3 - (Banded)	70	370 bc	30	400 bc
A5 - (Banded)	140	670 a	80	750 a
B2 - (Banded + Early Fertigation)	70	440 ab	70	510 ab
B4 – (Banded + Early Fertigation)	140	530 a	50	580 ab
C2 – (Banded + Late Fertigation)	70	220 bc	30	250bc
C4 – (Banded + Late Fertigation)	140	250 bc	40	280 bc
D1 – (Early + Late Fertigation)	70	450 ab	60	510 ab
D3 – (Banded + Early + Late Fertig.)	140	510 a	30	540 ab

Table 8. Nitrate measured in the soil profile under various fertilizer-N application strategies at Outlook, SK. after harvest of the 2018 crop year.

N-Management	Total N Applied	Soil Nitrate (0-120 cm)
	kg N ha^{-1}	
A1 - (Check)	0	66 e
A3 - (Banded)	70	83 bcde
A5 - (Banded)	140	193 a
B2 - (Banded + Early Fertigation)	70	54 de
B4 – (Banded + Early Fertigation)	140	112 bcd
C2 – (Banded + Late Fertigation)	70	22 e
C4 – (Banded + Late Fertigation)	140	46 e
D1 – (Early + Late Fertigation)	70	126 bc
D3 – (Banded + Early + Late Fertigation)	140	133 ab

Table 9. Estimated cumulative N_2O loss from various fertilizer-N application strategies at Outlook, SK. during the 2019 growing season.

N-Management	Total N Applied	Growing Season
	kg N ha^{-1}	g N_2O-N ha^{-1}
A1 - (Check)	0	360 c
A3 - (Banded)	70	400 c
A5 - (Banded)	140	800 a
B2 - (Banded + Early Fertigation)	70	440 bc
B4 – (Banded + Early Fertigation)	140	590 b
C2 – (Banded + Late Fertigation)	70	430 bc
C4 – (Banded + Late Fertigation)	140	580 b
D1 – (Early + Late Fertigation)	70	440 bc
D3 – (Banded + Early + Late Fertig.)	140	440 bc

Table 10. Mean estimated cumulative N_2O loss from various fertilizer-N application strategies at Outlook, SK. over three (2017-19) growing seasons.

N-Management	Total N Applied	Mean N_2O loss
	kg N ha^{-1}	g N_2O-N ha^{-1}
A1 - (Check)	0	135 c
A3 - (Banded)	70	400 bc
A5 - (Banded)	140	750 a
B2 - (Banded + Early Fertigation)	70	506 ab
B4 – (Banded + Early Fertigation)	140	580 ab
C2 – (Banded + Late Fertigation)	70	252 bc
C4 – (Banded + Late Fertigation)	140	282 bc
D1 – (Early + Late Fertigation)	70	506 ab
D3 – (Banded + Early + Late Fertig.)	140	537 ab

Table 11. Three-year cumulative yield intensity values calculated for various fertilizer-N application strategies at Outlook, SK.

N-Management	Total N Applied	Yield Intensity
	kg N ha^{-1}	(g N_2O-N kg $seed^{-1}$)
A1 - (Check)	0	0.082 c
A3 - (Banded)	70	0.097 bc
A5 - (Banded)	140	0.132 a
B2 - (Banded + Early Fertigation)	70	0.105 ab
B4 – (Banded + Early Fertigation)	140	0.131 a
C2 – (Banded + Late Fertigation)	70	0.088 bc
C4 – (Banded + Late Fertigation)	140	0.104 abc
D1 – (Early + Late Fertigation)	70	0.100 bc
D3 – (Banded + Early + Late	140	0.110 ab

Appendix ii - Figures.

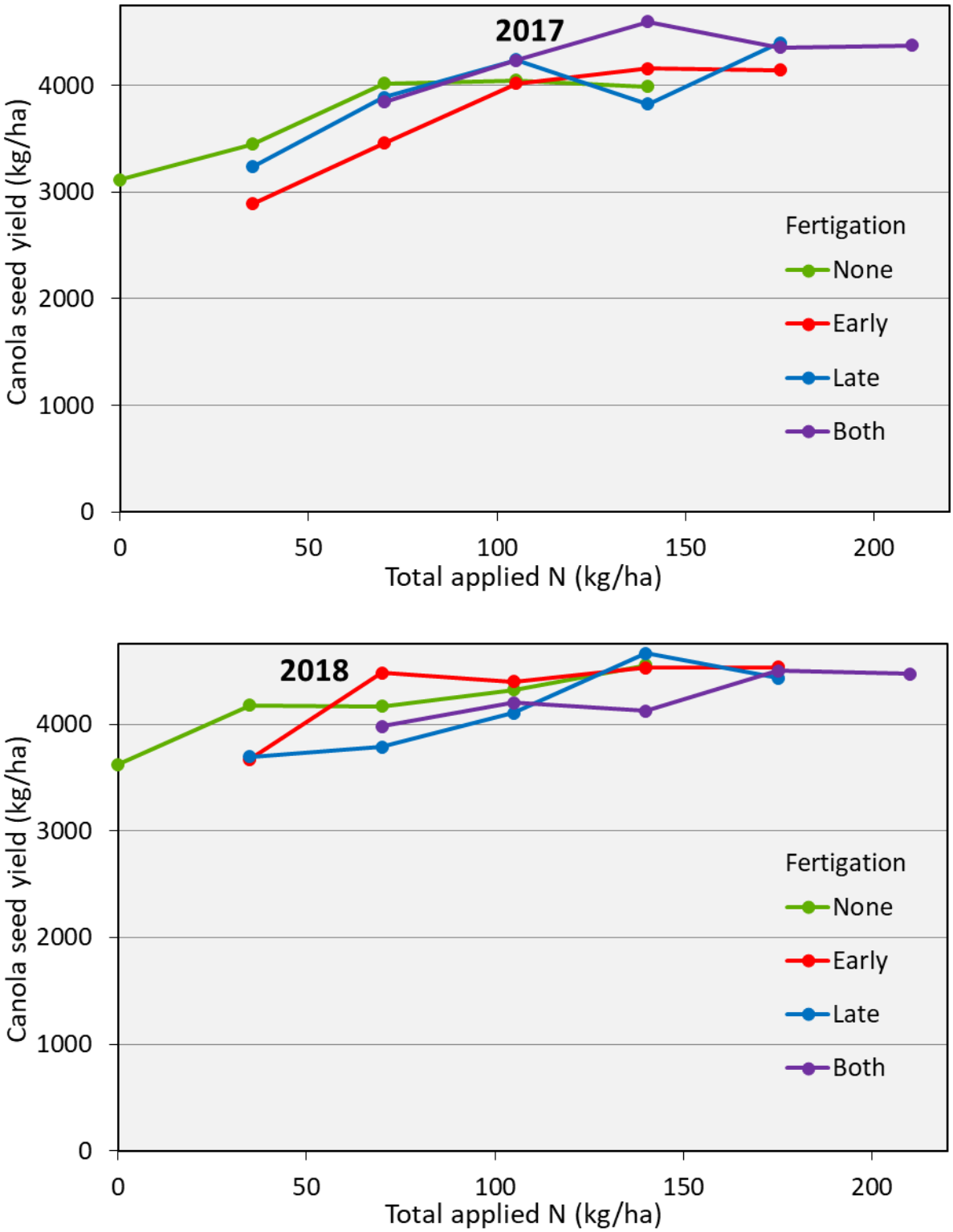
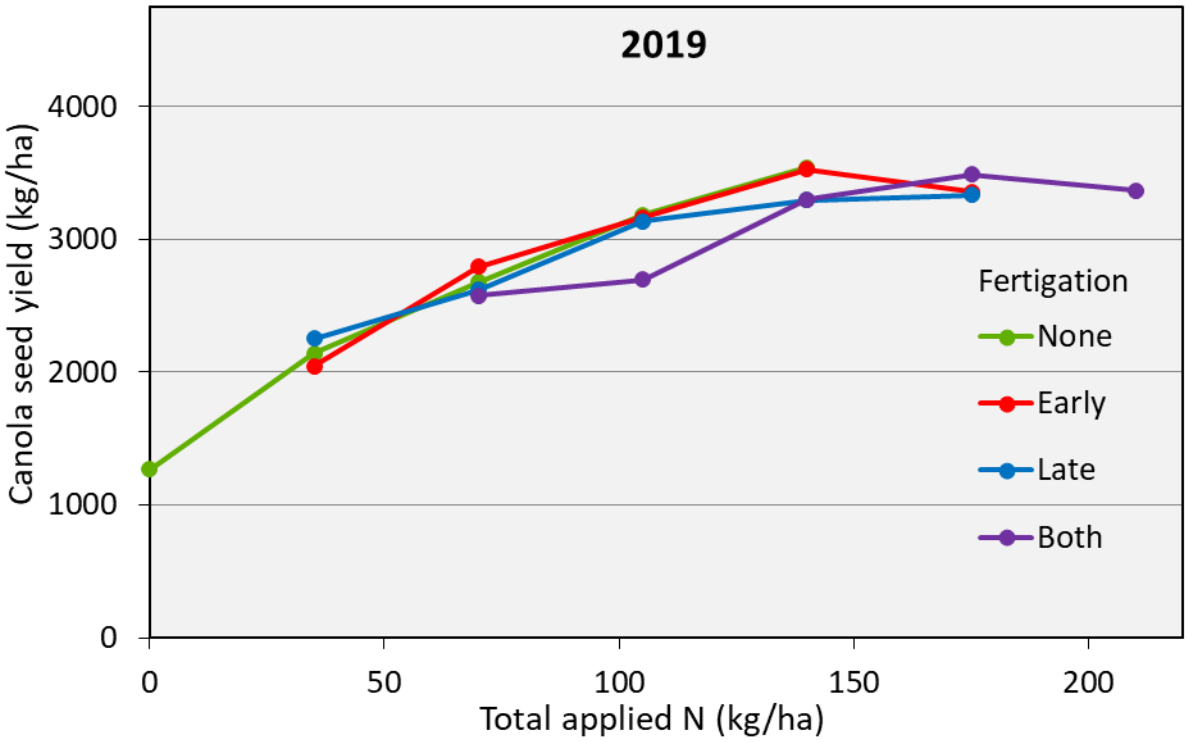


Figure 1. Canola seed yield, adjusted to 8.5% moisture; 2017 - top, and 2018 - bottom. Cont . . .



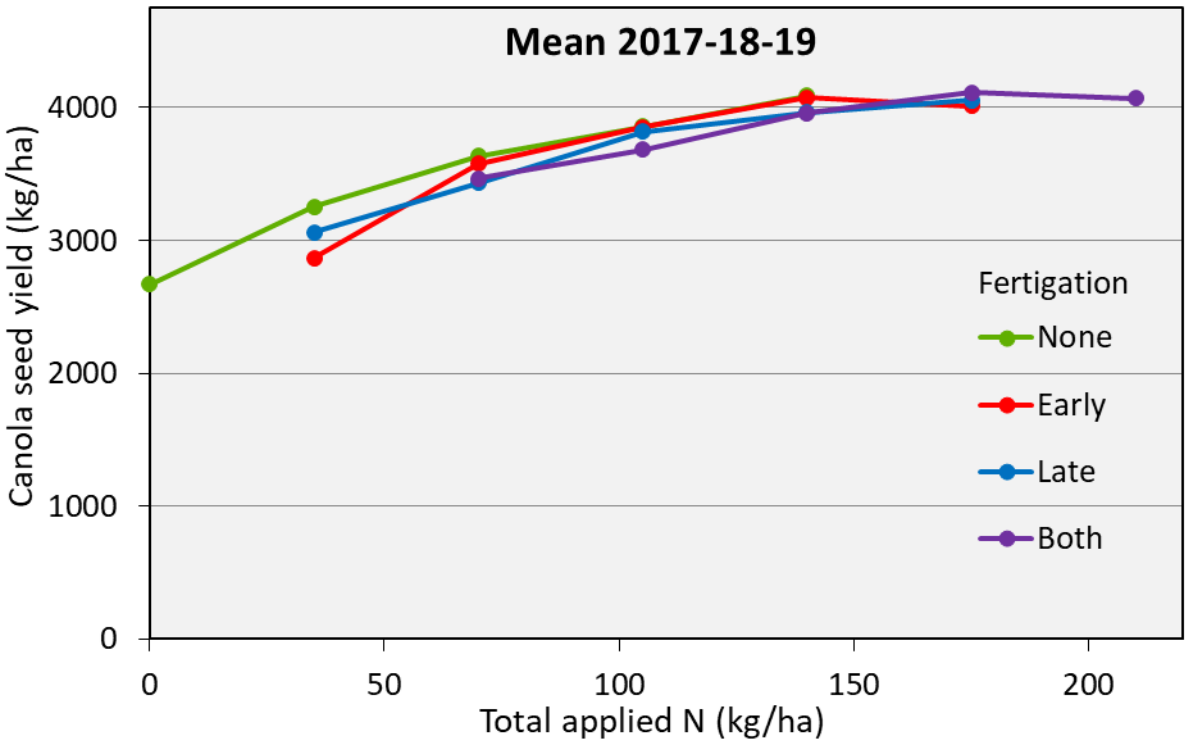
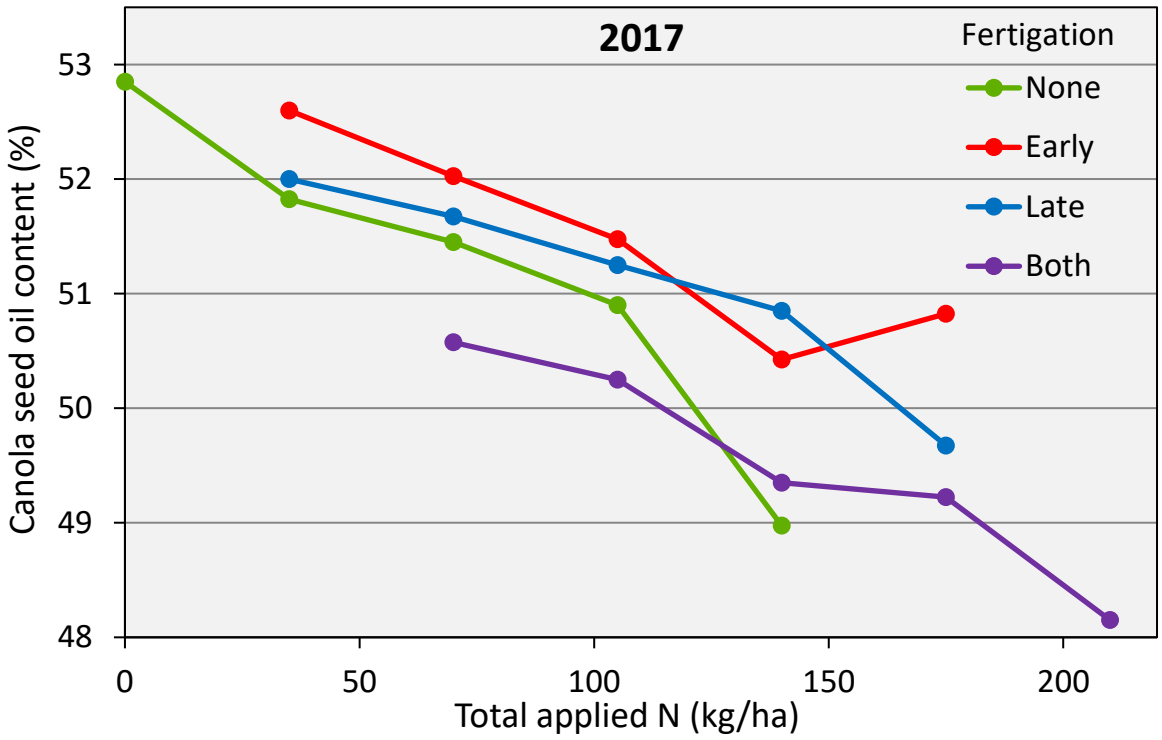


Figure 1. (cont.) Canola seed yield, adjusted to 8.5% moisture; 2019 - top, and mean of 2017, 2018, and 2019 - bottom.



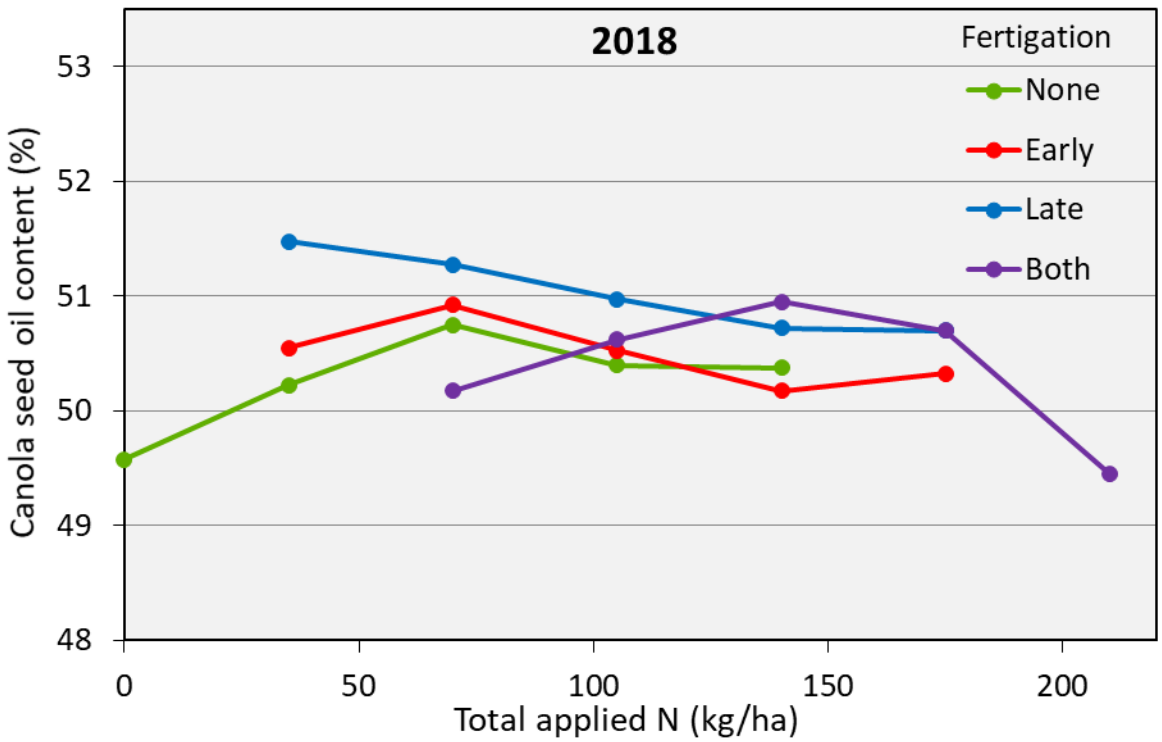
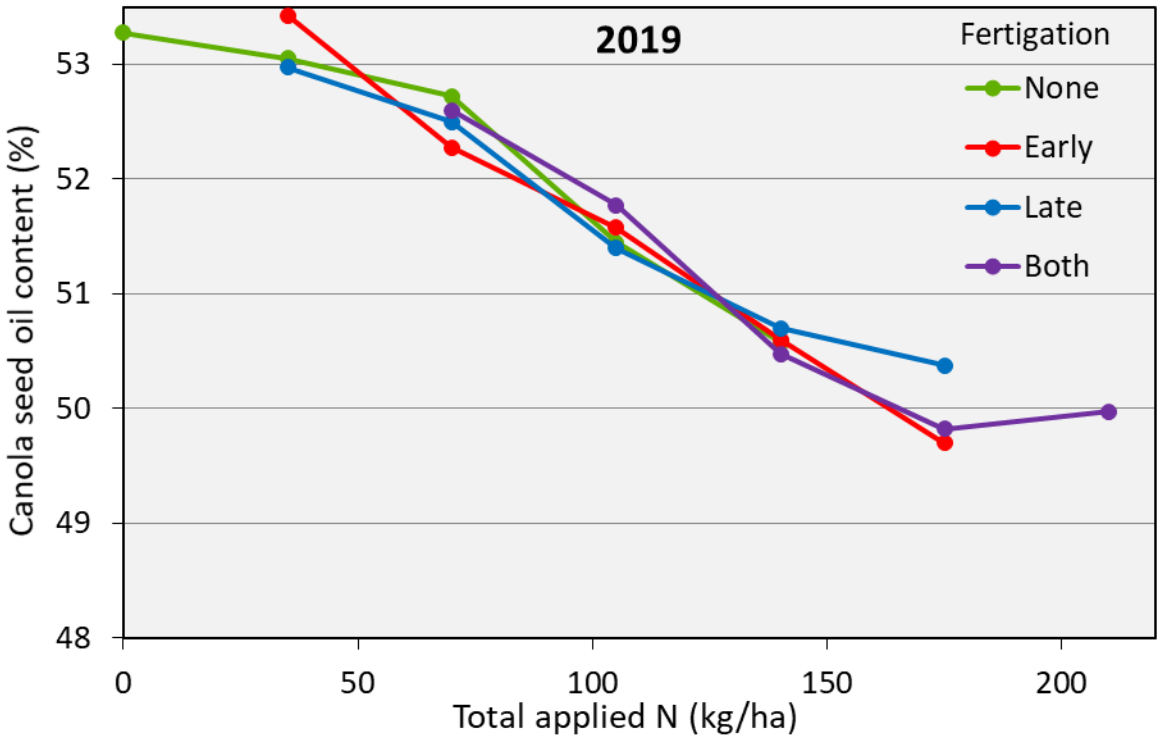


Figure 2. Canola seed oil content; 2017 - top, and 2018 - bottom. Cont . . .



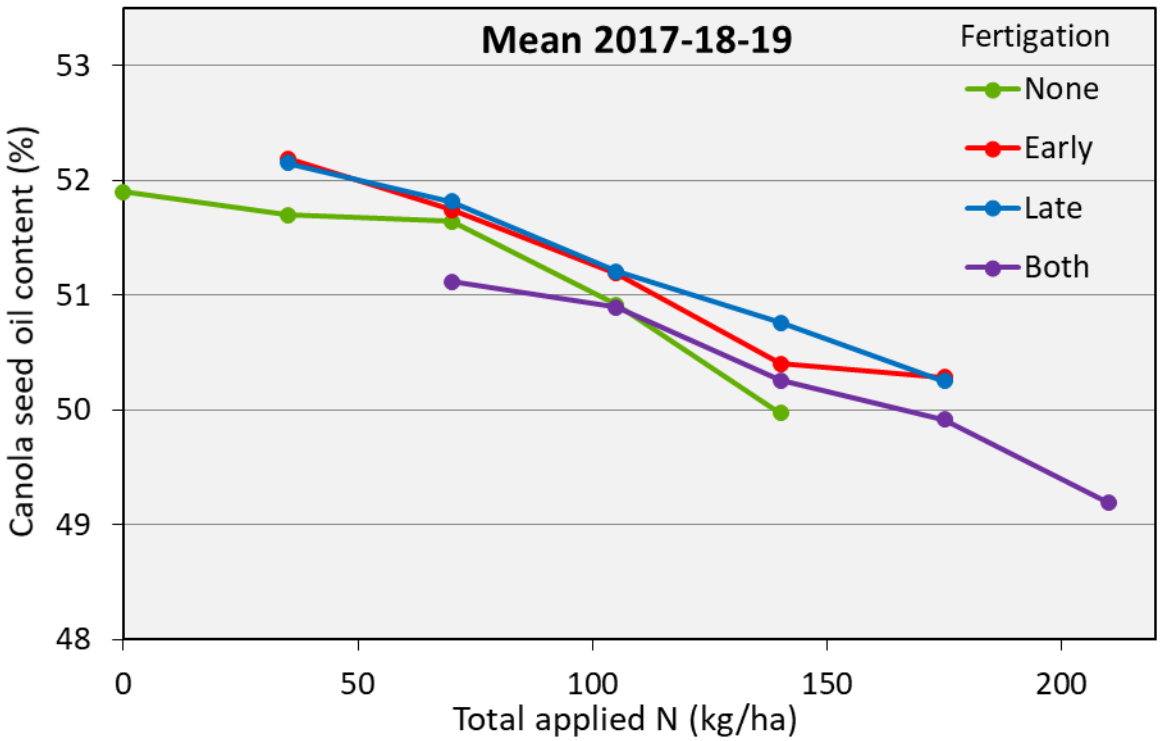


Figure 2. (cont.) Canola seed oil content; 2019 - top, and mean of 2017, 2018, and 2019 - bottom.

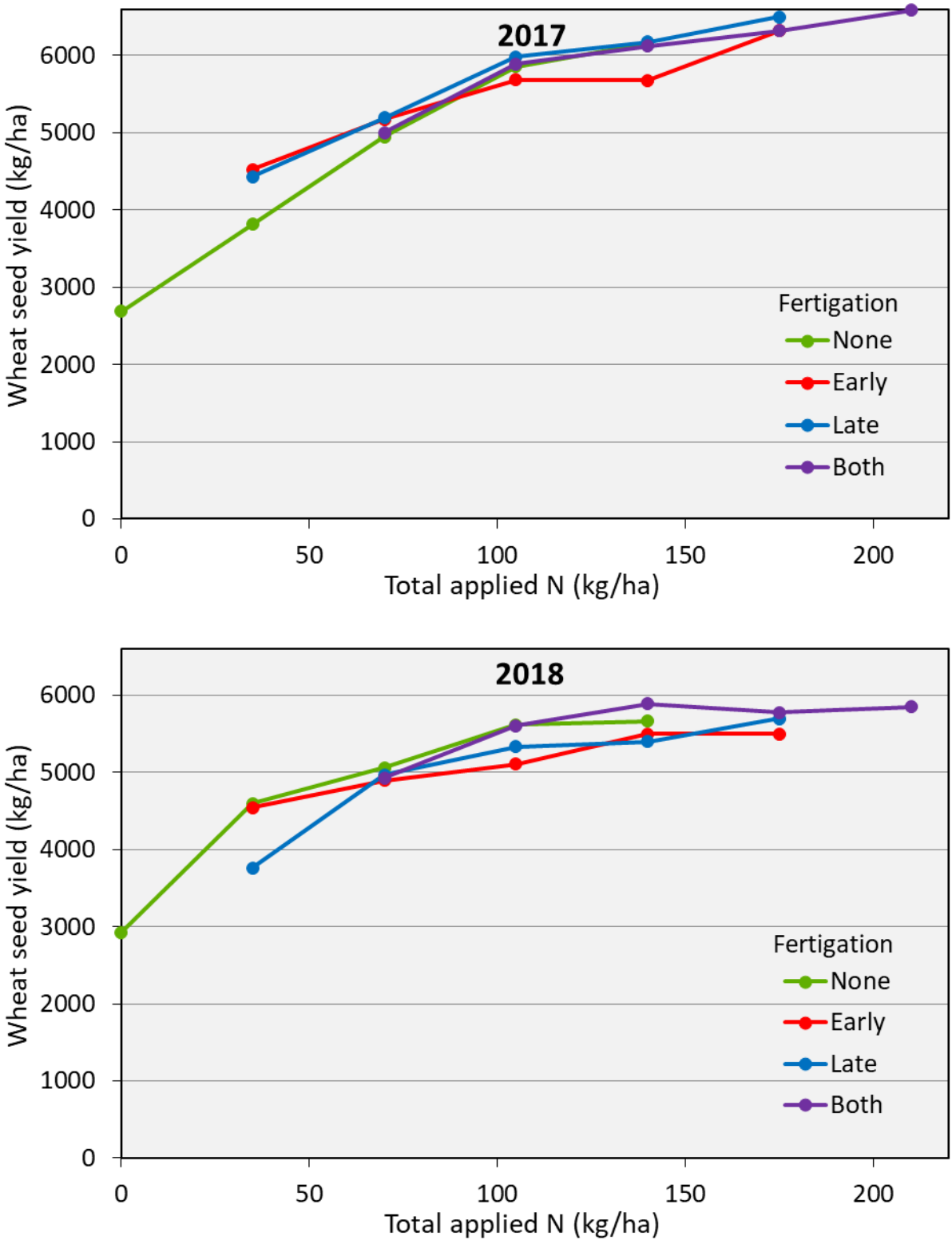


Figure 3. Wheat grain yield, adjusted to 13.5% moisture; 2017 - top, and 2018 - bottom. Cont . . .

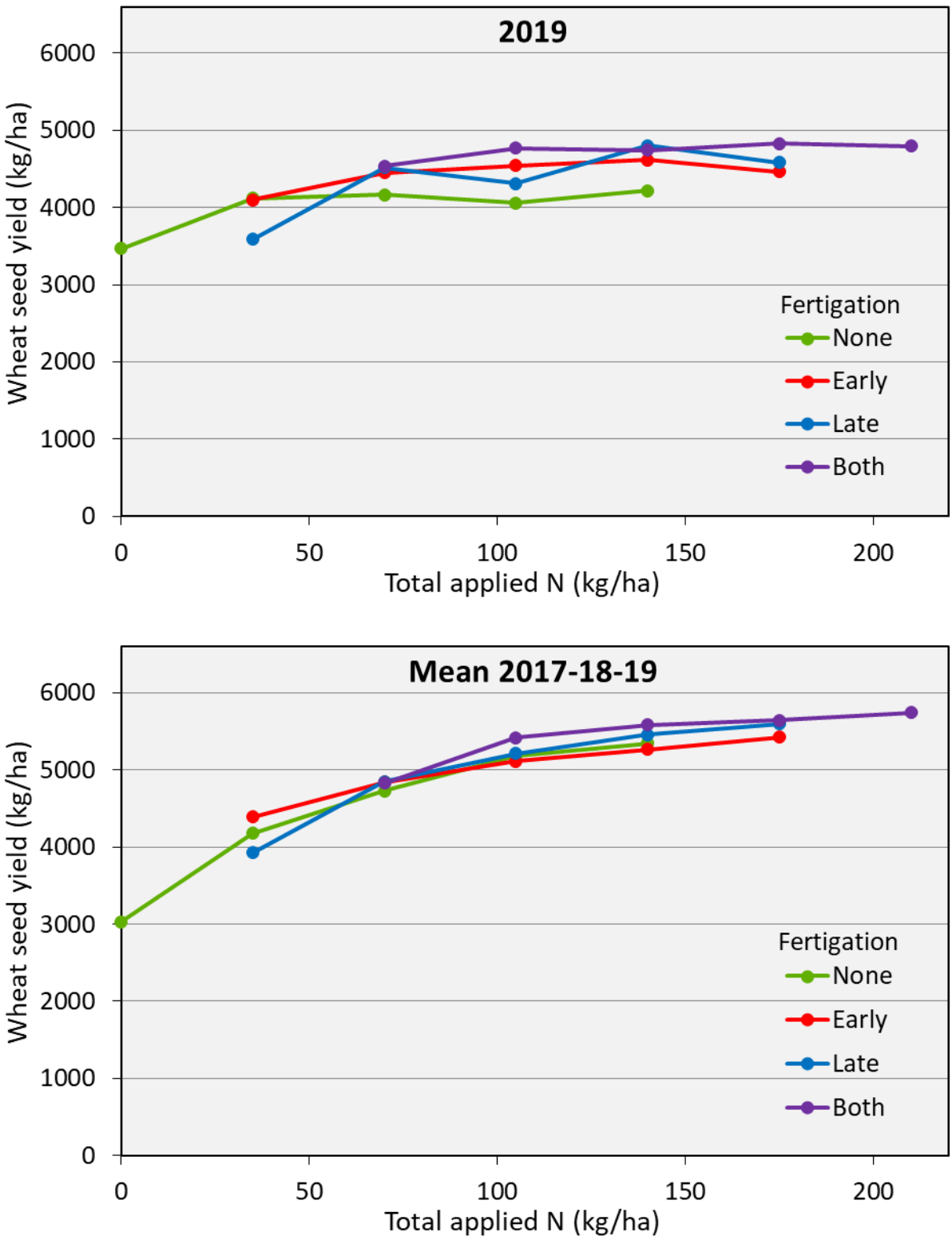


Figure 3. (cont.) Wheat grain yield, adjusted to 13.5% moisture; 2019 - top, and mean of 2017, 2018, and 2019 - bottom.

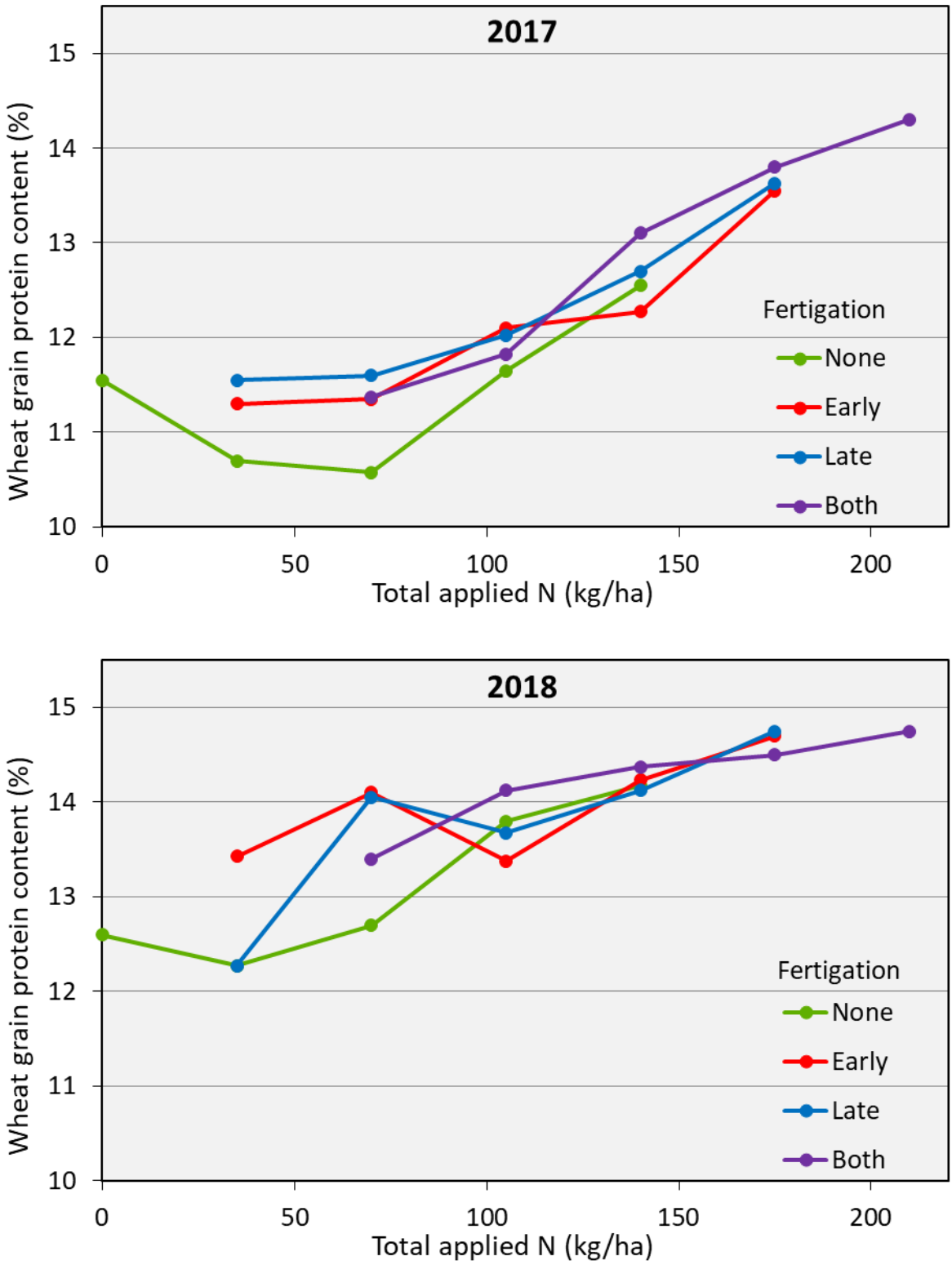


Figure 4. Wheat grain protein content; 2017 - top, and 2018 - bottom. Cont . . .

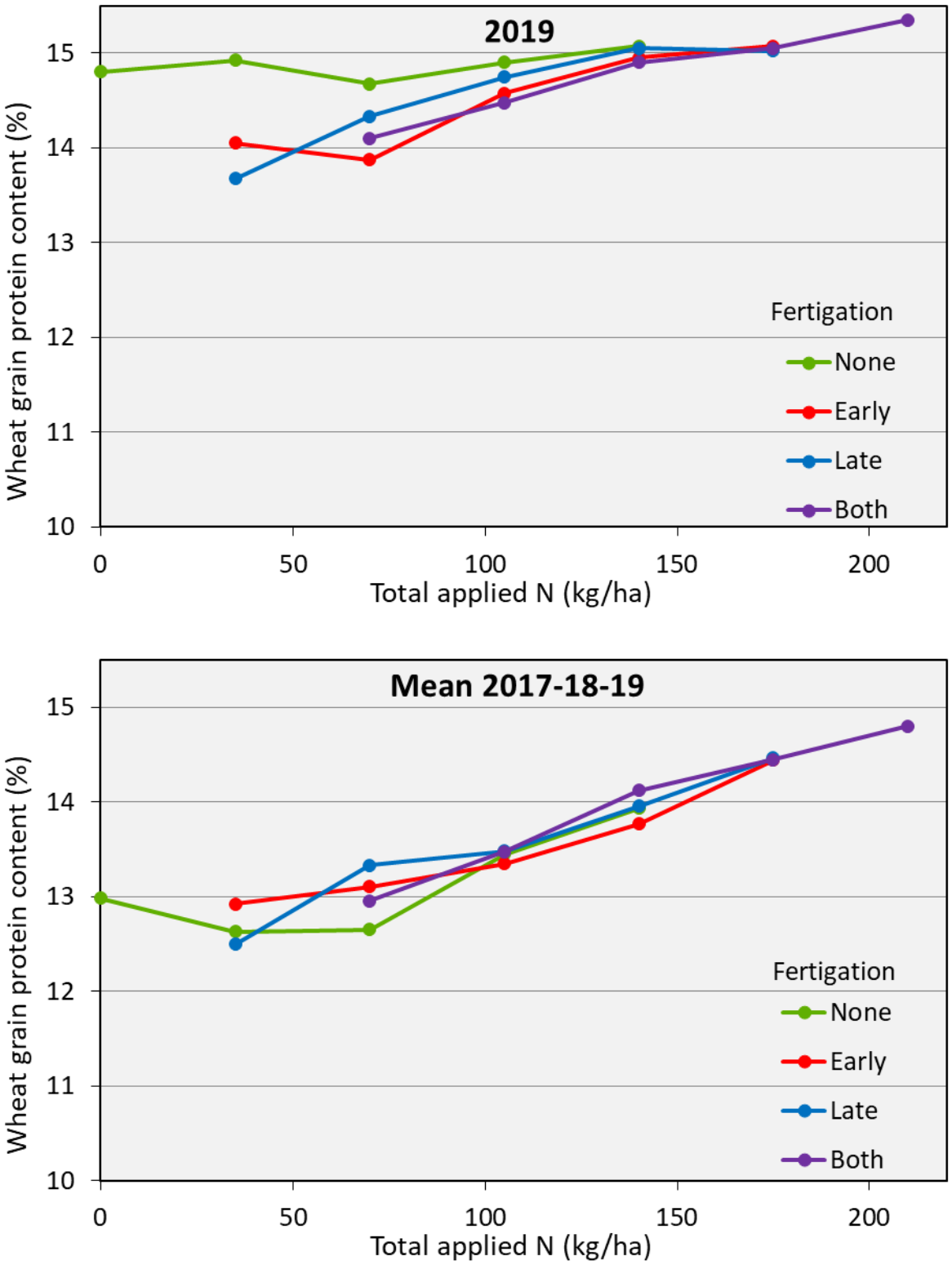


Figure 4. (cont.) Wheat grain protein content; 2019 - top, and mean of 2017, 2018, and 2019 - bottom.

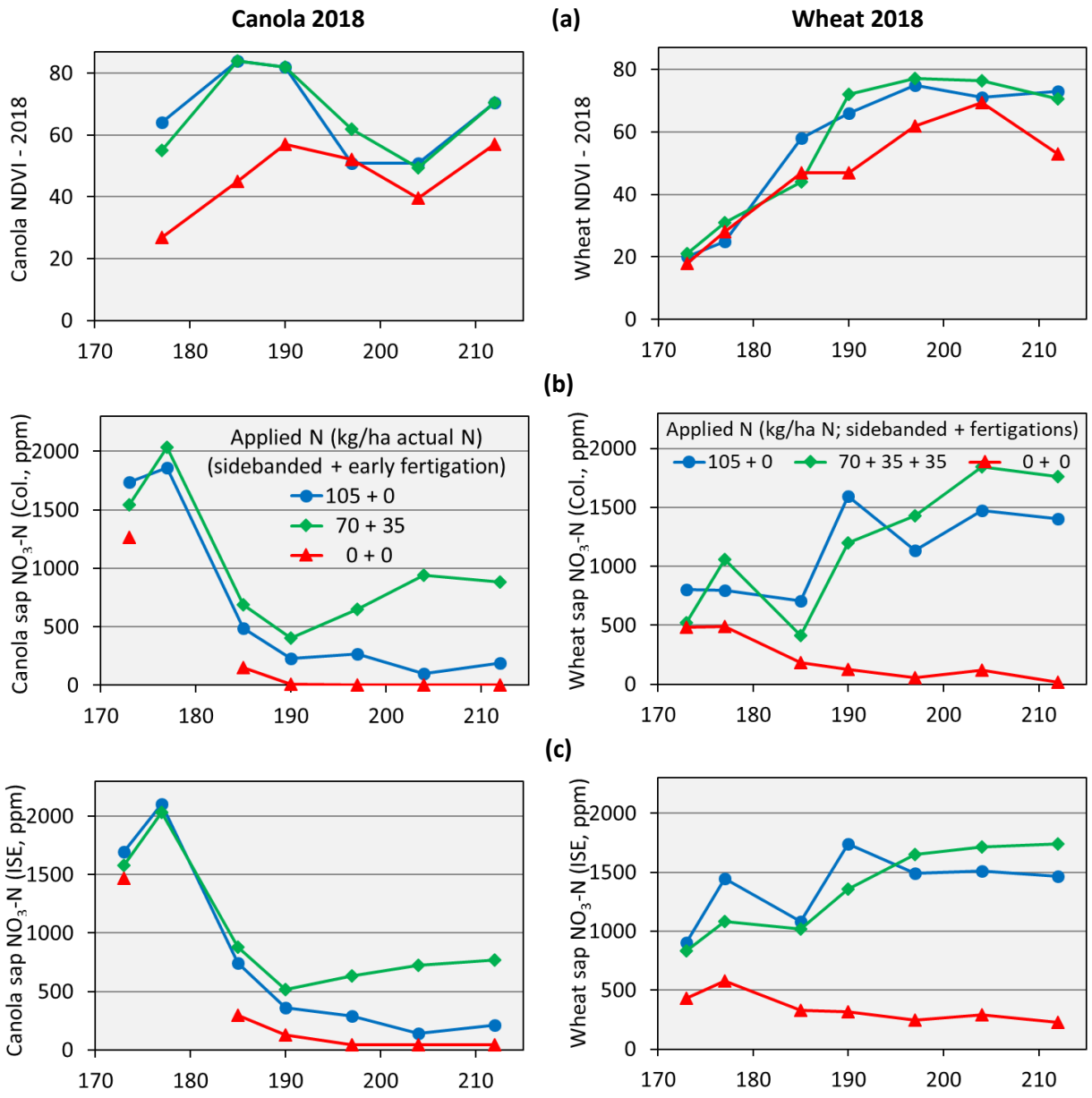


Figure 5. Canola (left) and wheat (right) N tests in three selected treatments on seven dates from June 20/22 to July 31, 2018: (a) NDVI; petiole/stem sap nitrate with on-site determination by (b) colorimetric; and (c) ion selective electrode methods; (d) petiole/stem extractable from dried tissue (lab); and (e) leaf blade total N. Legend applies to all graphs. (cont. . . .)

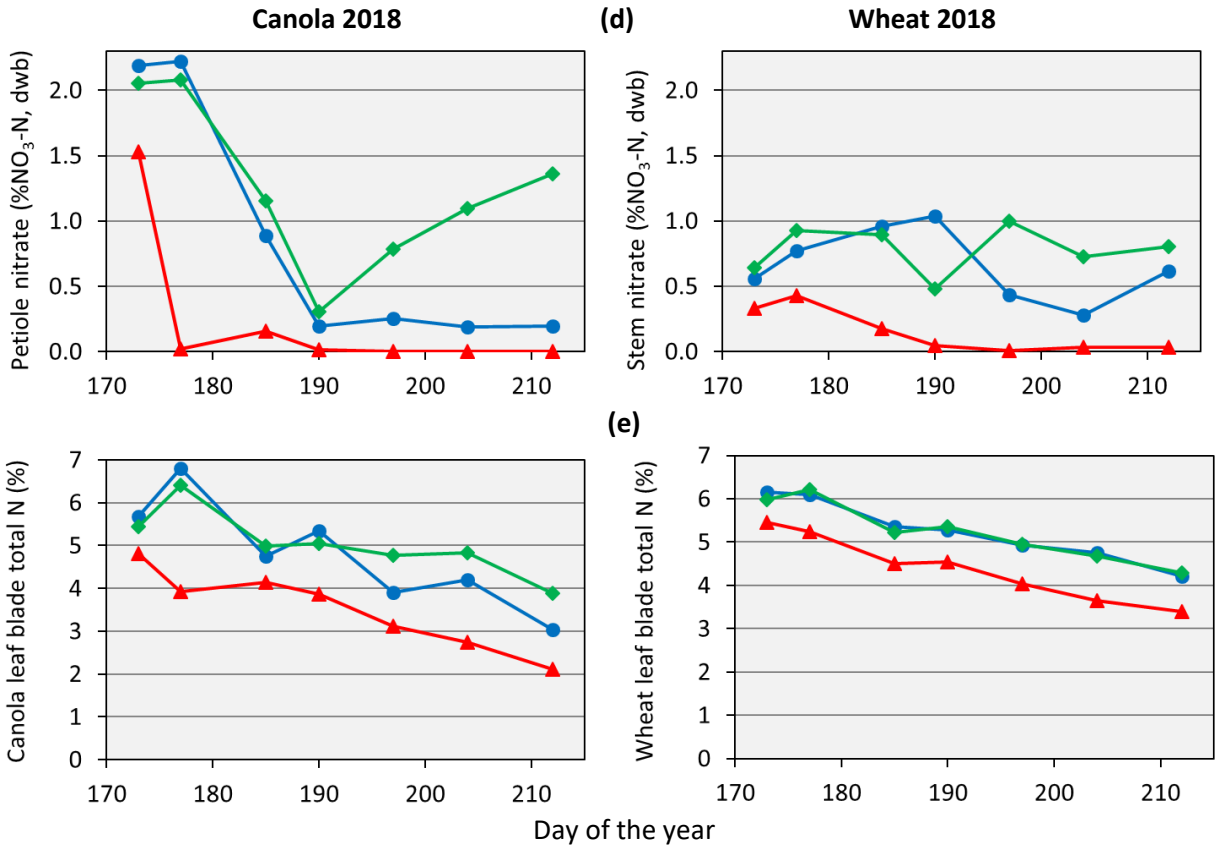


Figure 5 (cont.). Canola (left) and wheat (right) N tests in three selected treatments on seven dates from June 20/22 to July 31, 2018: (a) NDVI; petiole/stem sap nitrate with on-site determination by (b) colorimetric; and (c) ion selective electrode methods; (d) petiole/stem extractable from dried tissue (lab); and (e) leaf blade total N. Legend applies to all graphs.

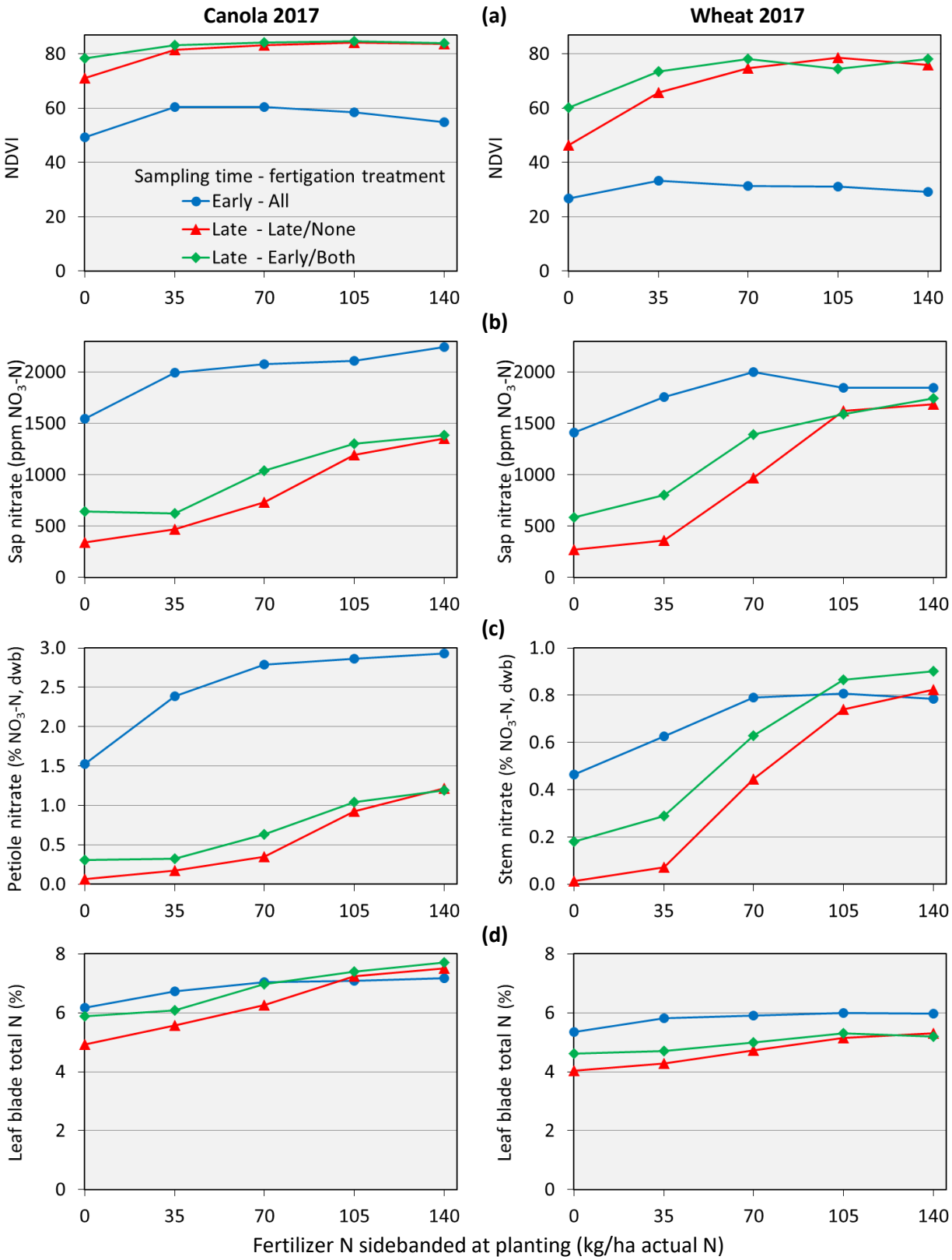


Figure 6. Plant N measurements in 2017 studies, for canola (left) and wheat (right): (a) NDVI, (b) petiole/stem sap nitrate, (c) petiole/stem nitrate in dried tissue, and (d) leaf blade total N. Legend at top left applies to all graphs.

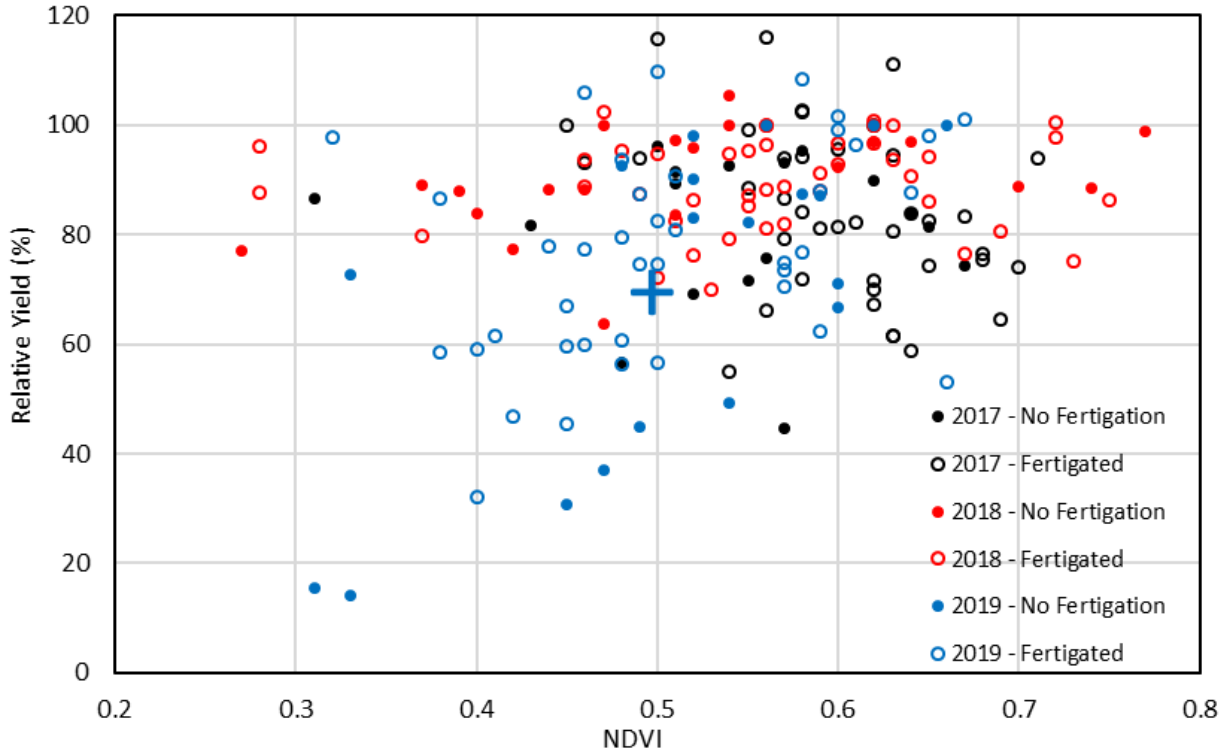


Figure 7. Relationship between early NDVI readings and relative yield of canola.

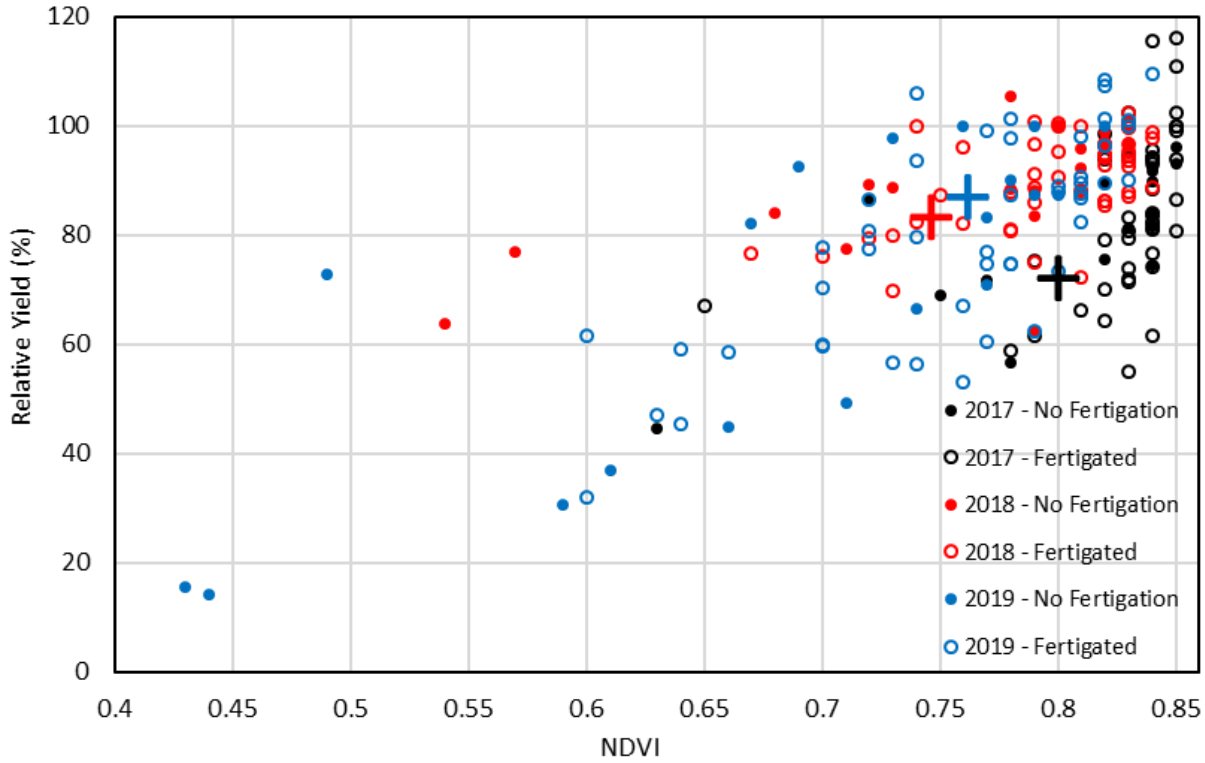


Figure 8. Relationship between late NDVI readings and relative yield of canola.

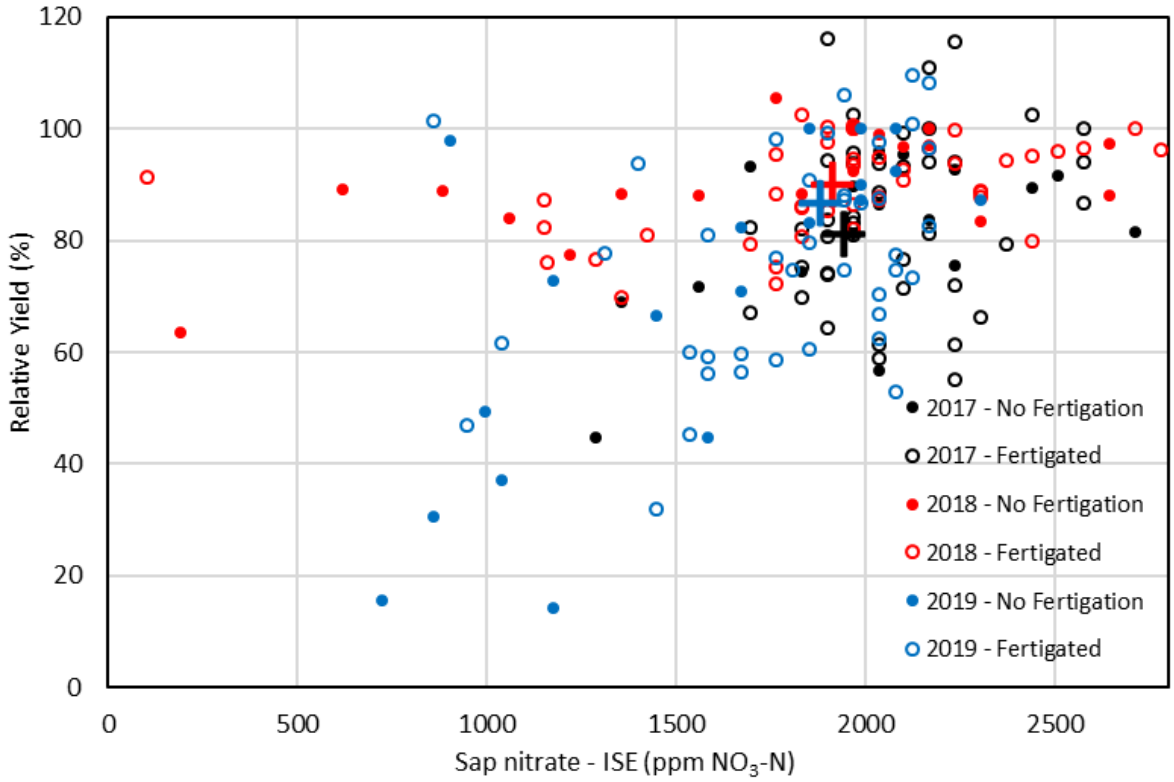


Figure 9. Relationship between early sap nitrate concentration (ISE method) and relative yield of canola.

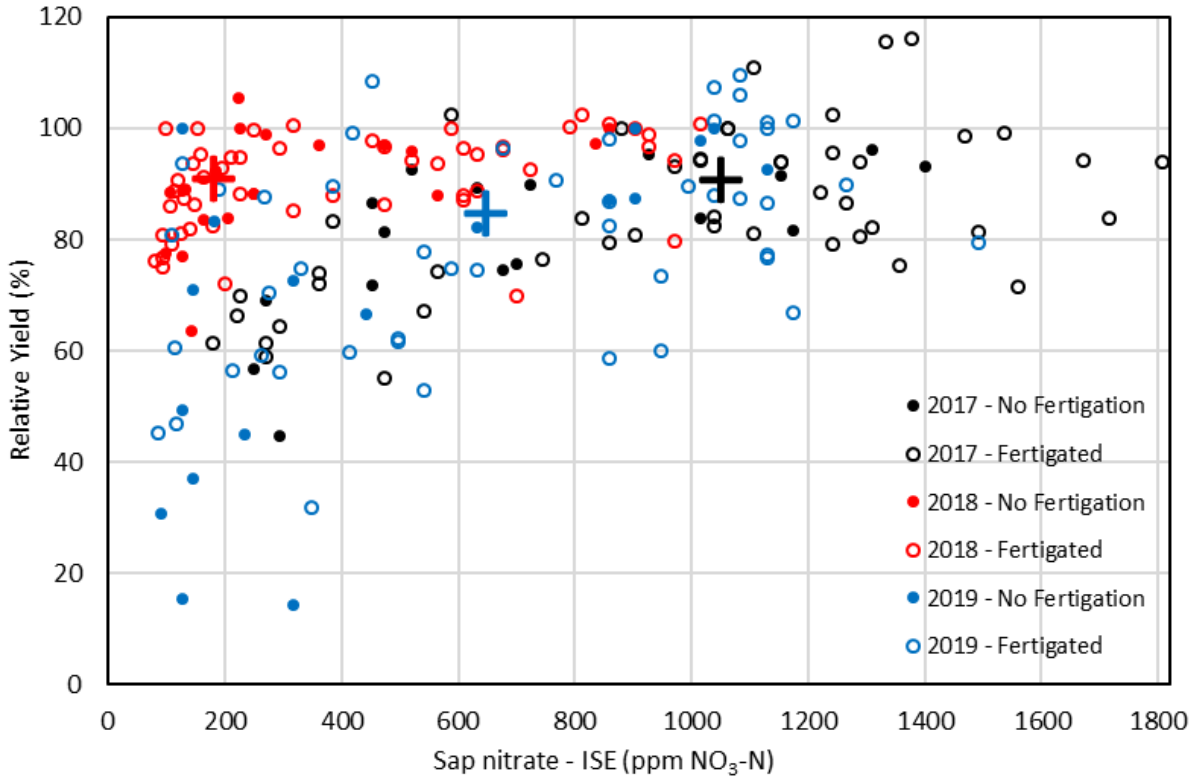


Figure 10. Relationship between late sap nitrate concentration (ISE method) and relative yield of canola.

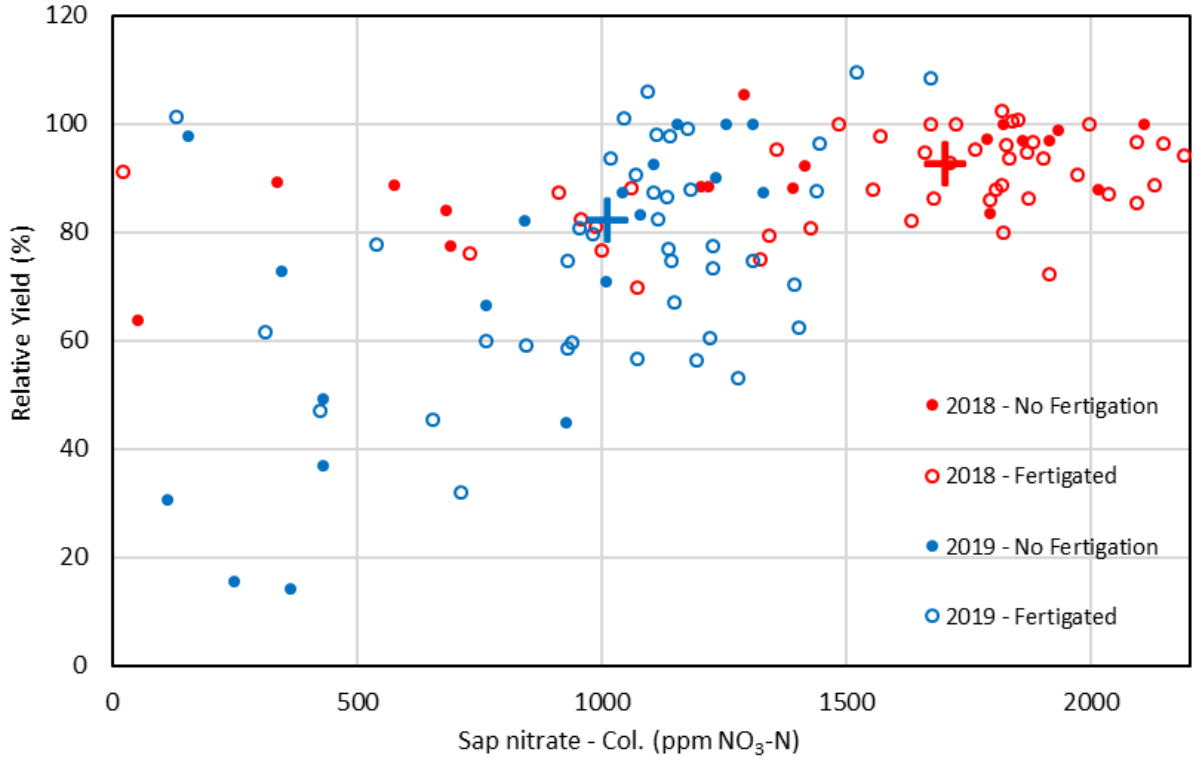


Figure 11. Relationship between early sap nitrate (colorimetric method) and relative yield of canola.

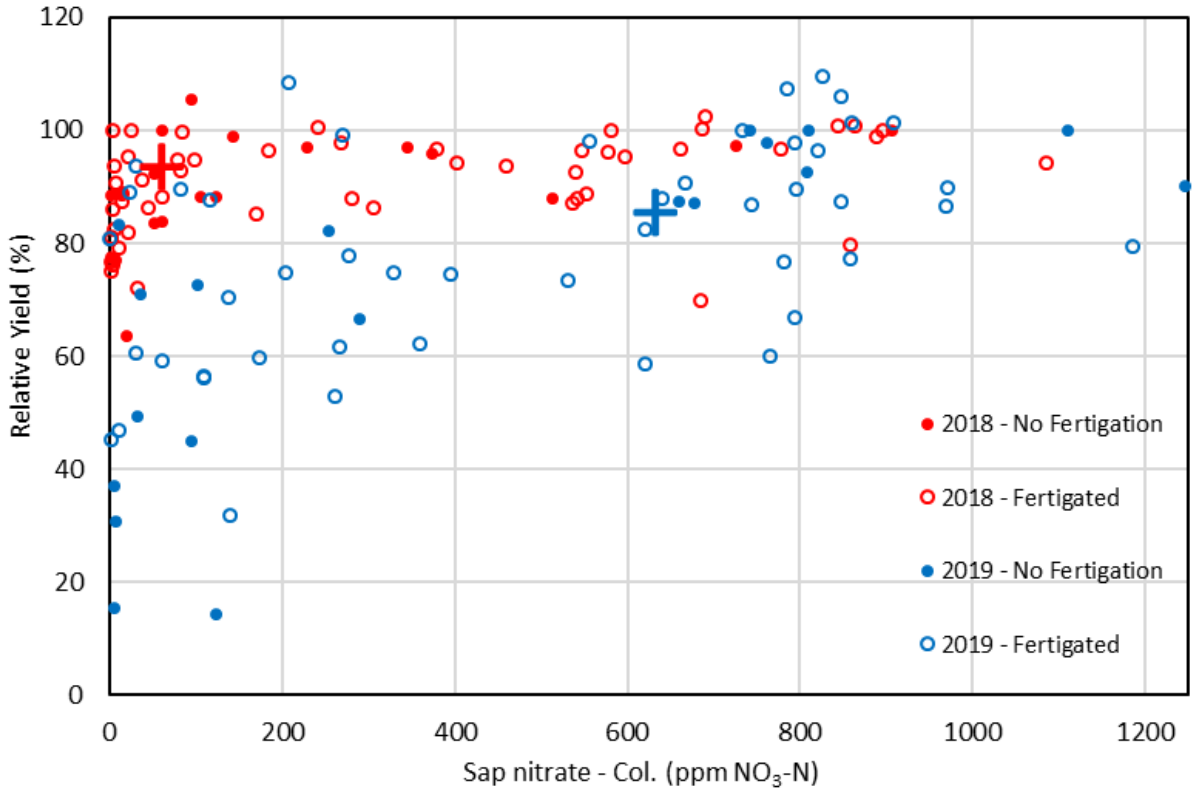


Figure 112. Relationship between late sap nitrate (colorimetric method) and relative yield of canola.

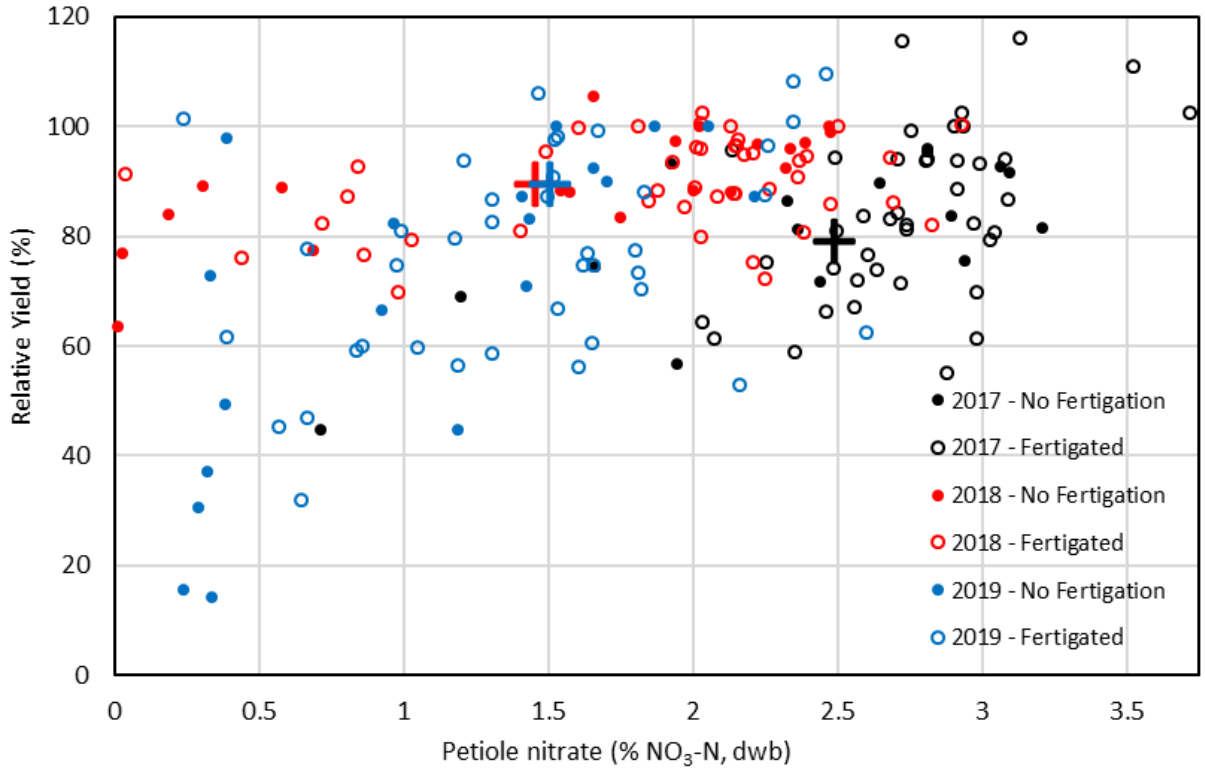


Figure 13. Relationship between early petiole nitrate concentration and relative yield of canola.

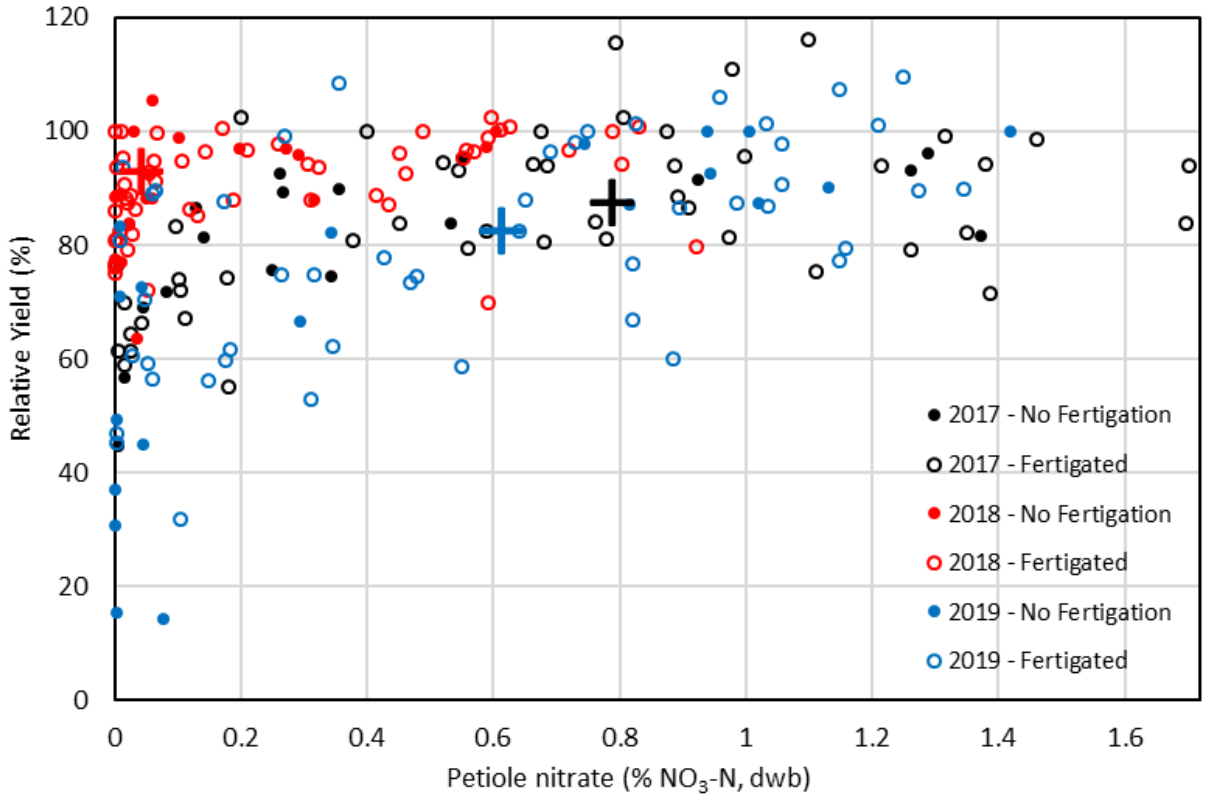


Figure 14. Relationship between early petiole nitrate concentration and relative yield of canola.

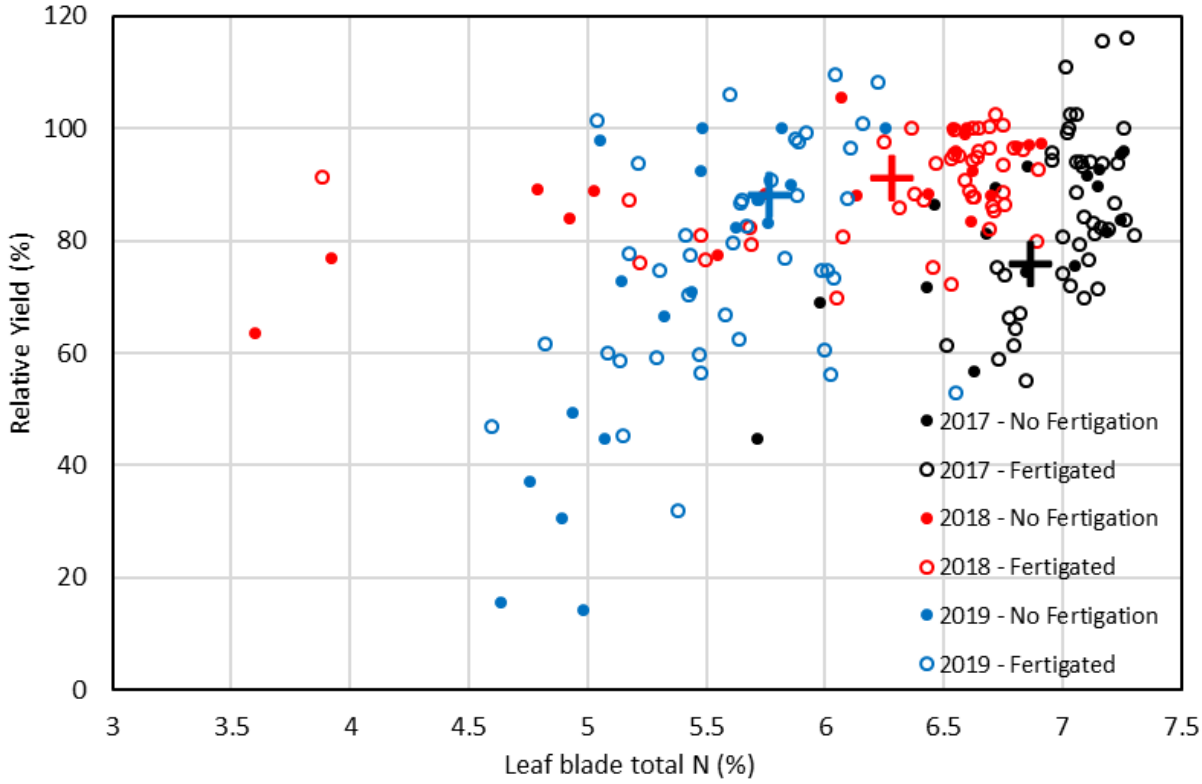


Figure 15. Relationship between early leaf blade total N concentration and relative yield of canola.

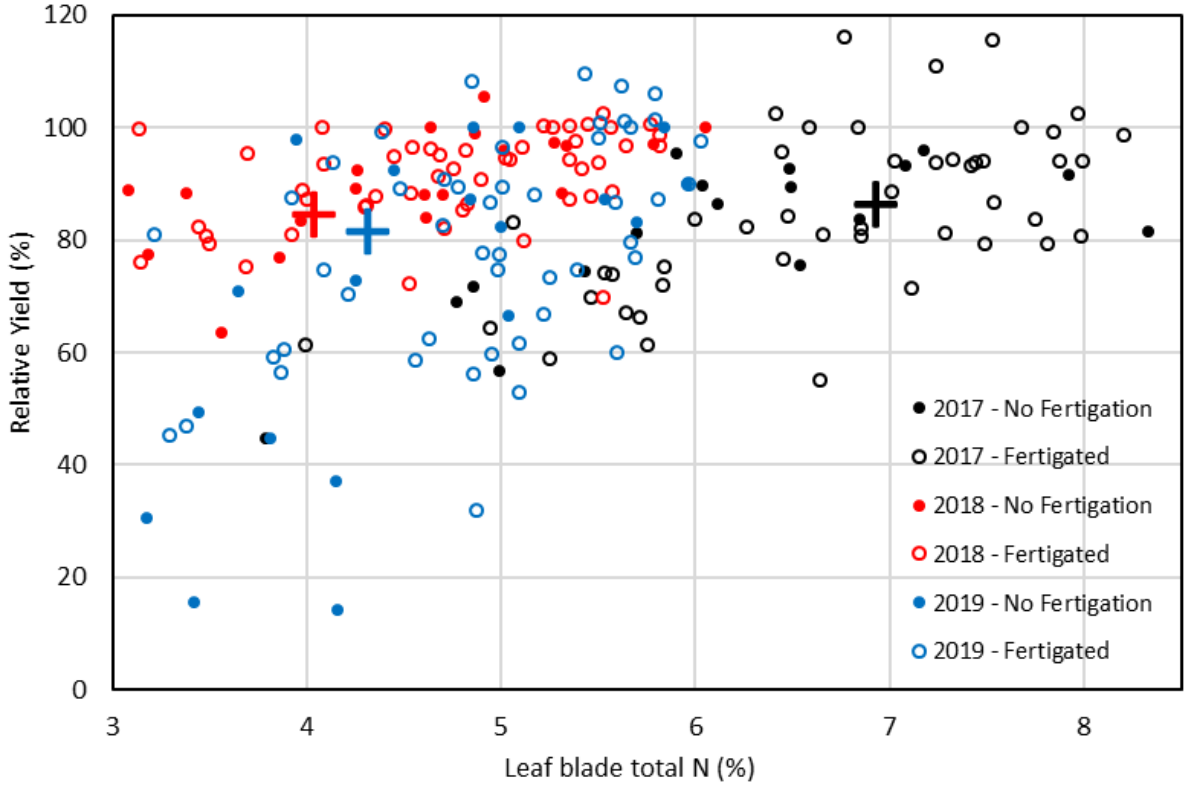


Figure 16. Relationship between late leaf blade total N concentration and relative yield of canola.

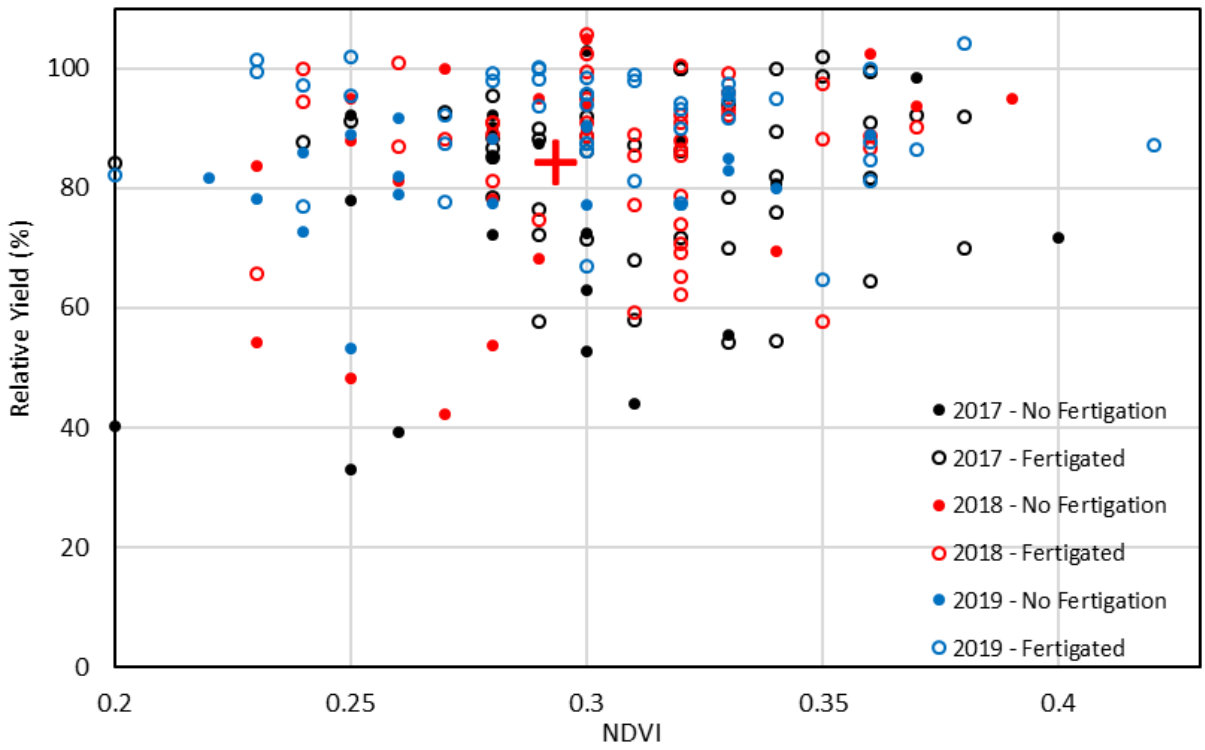


Figure 17. Relationship between early NDVI readings and relative yield of wheat.

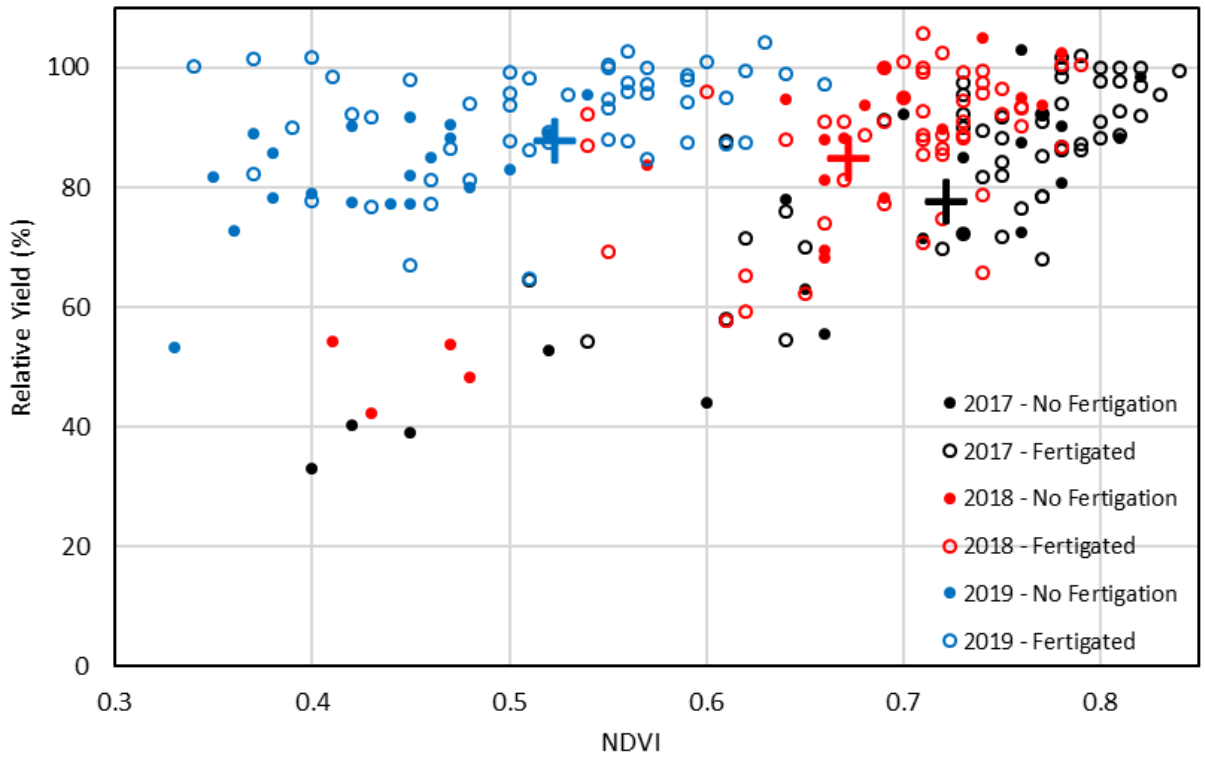


Figure 18. Relationship between late NDVI readings and relative yield of wheat.

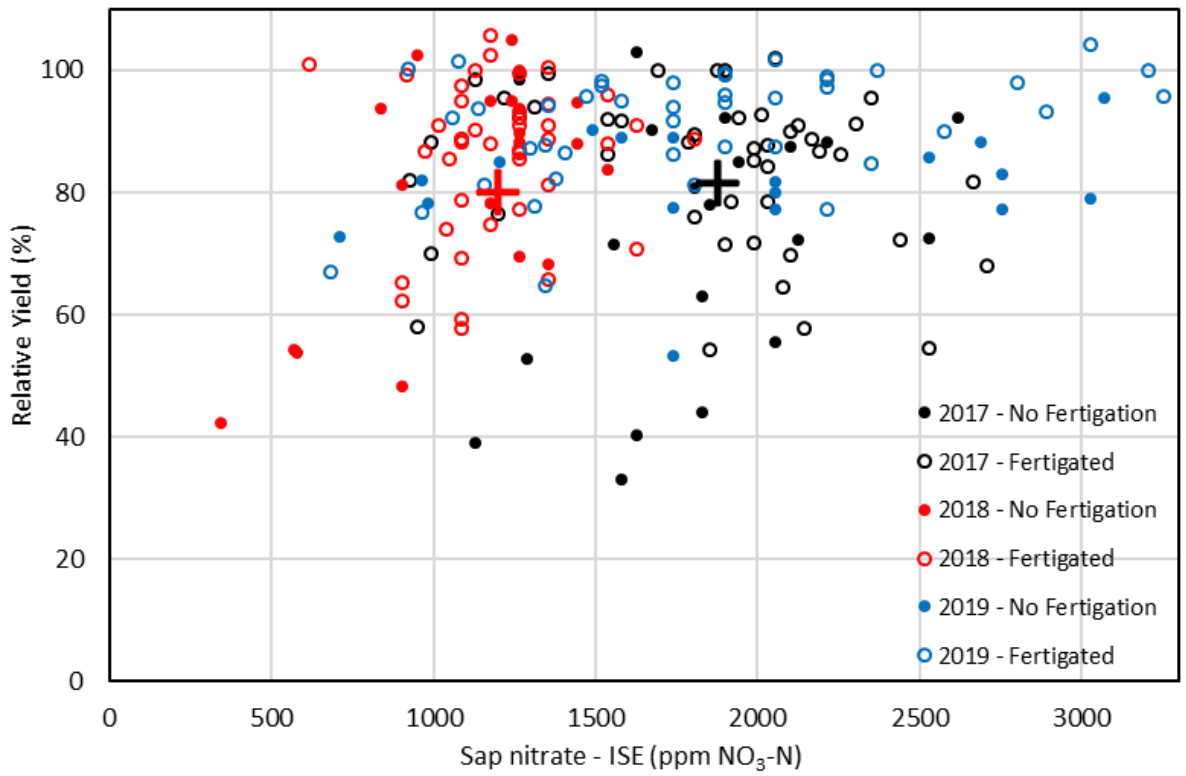


Figure 19. Relationship between early sap nitrate concentration (ISE method) and relative yield - wheat.

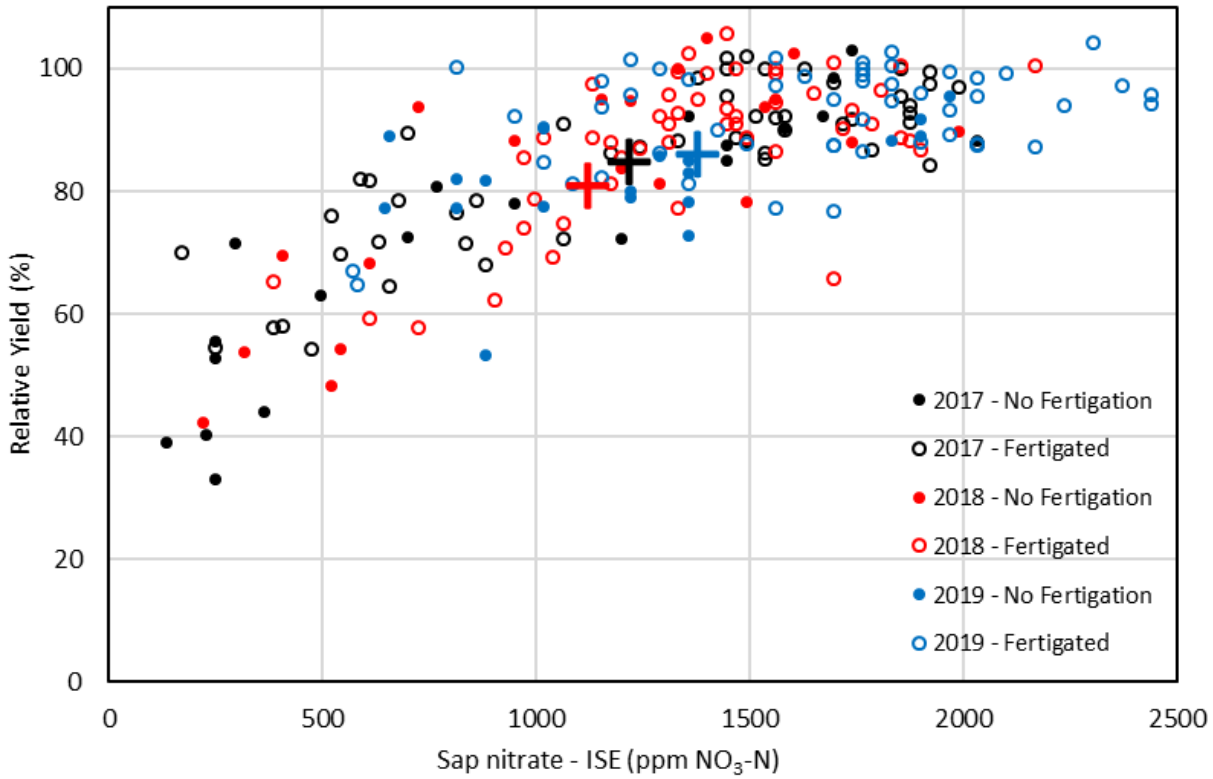


Figure 20. Relationship between late sap nitrate concentration (ISE method) and relative yield of wheat.

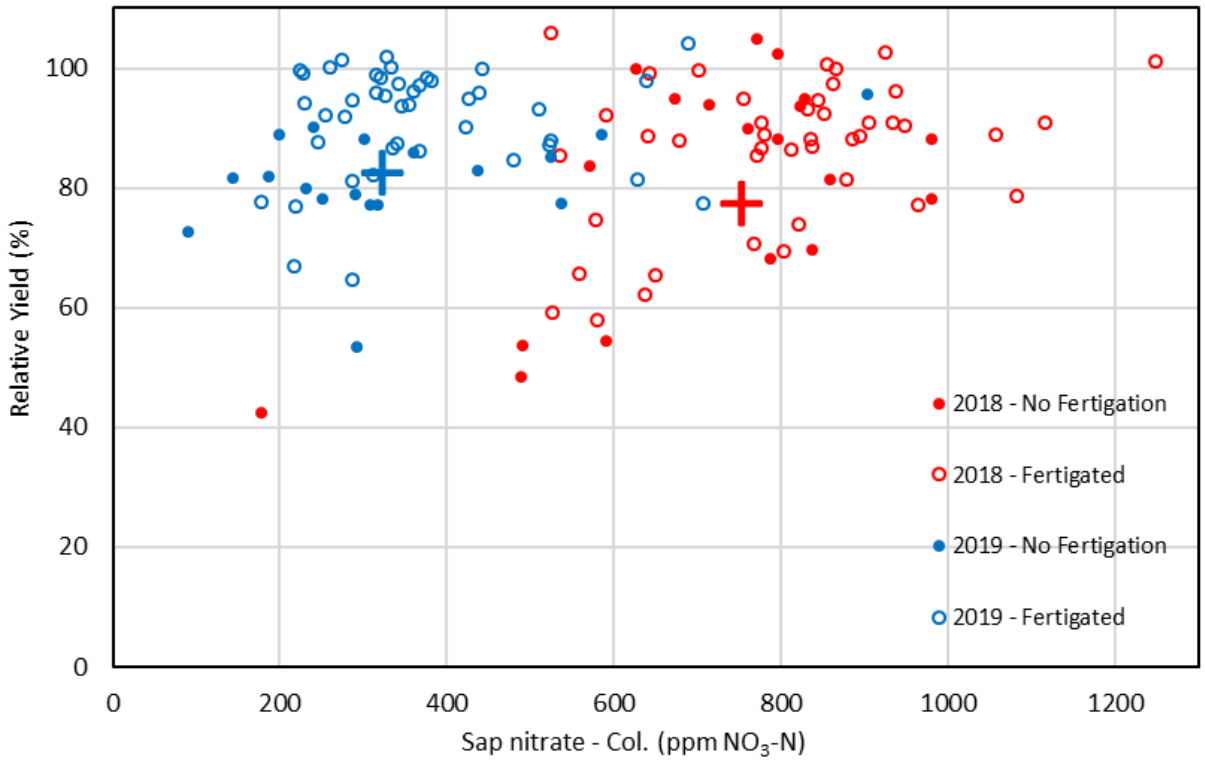


Figure 21. Relationship between early sap nitrate (colorimetric method) and relative yield of wheat.

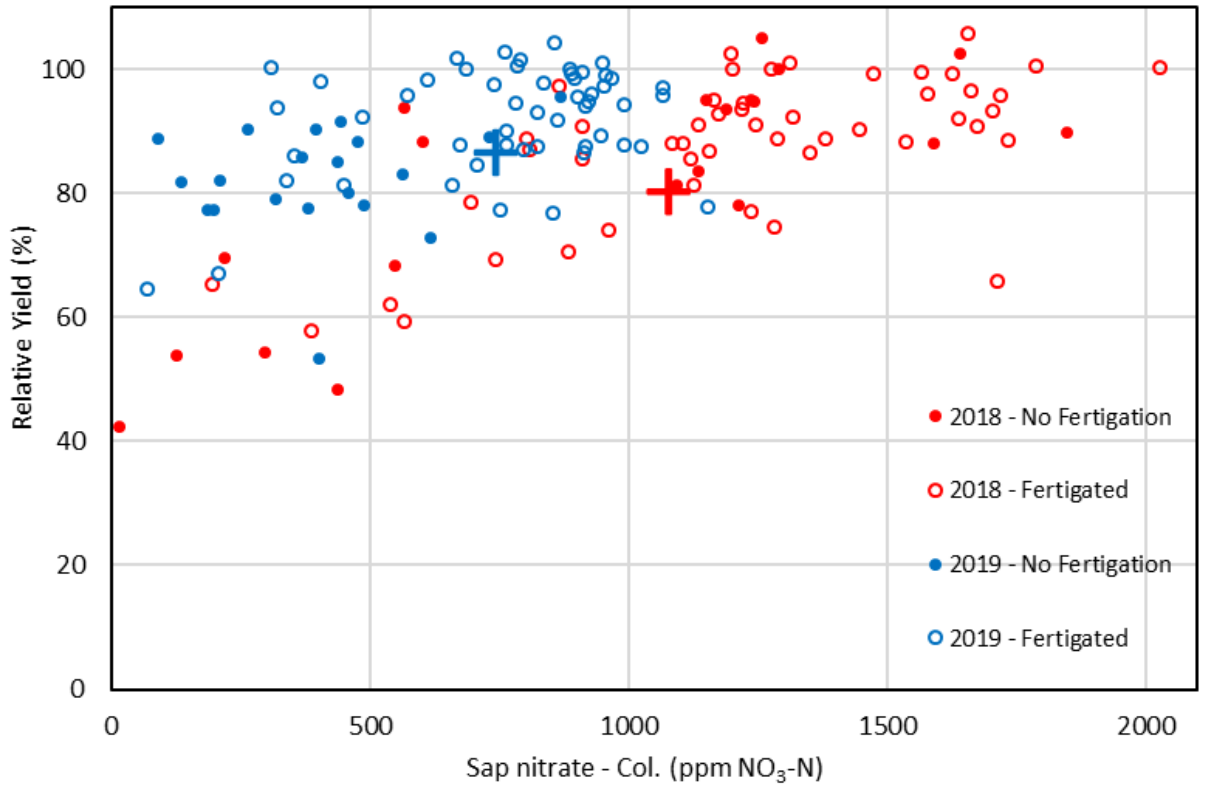


Figure 22. Relationship between late sap nitrate (colorimetric method) and relative yield of wheat.

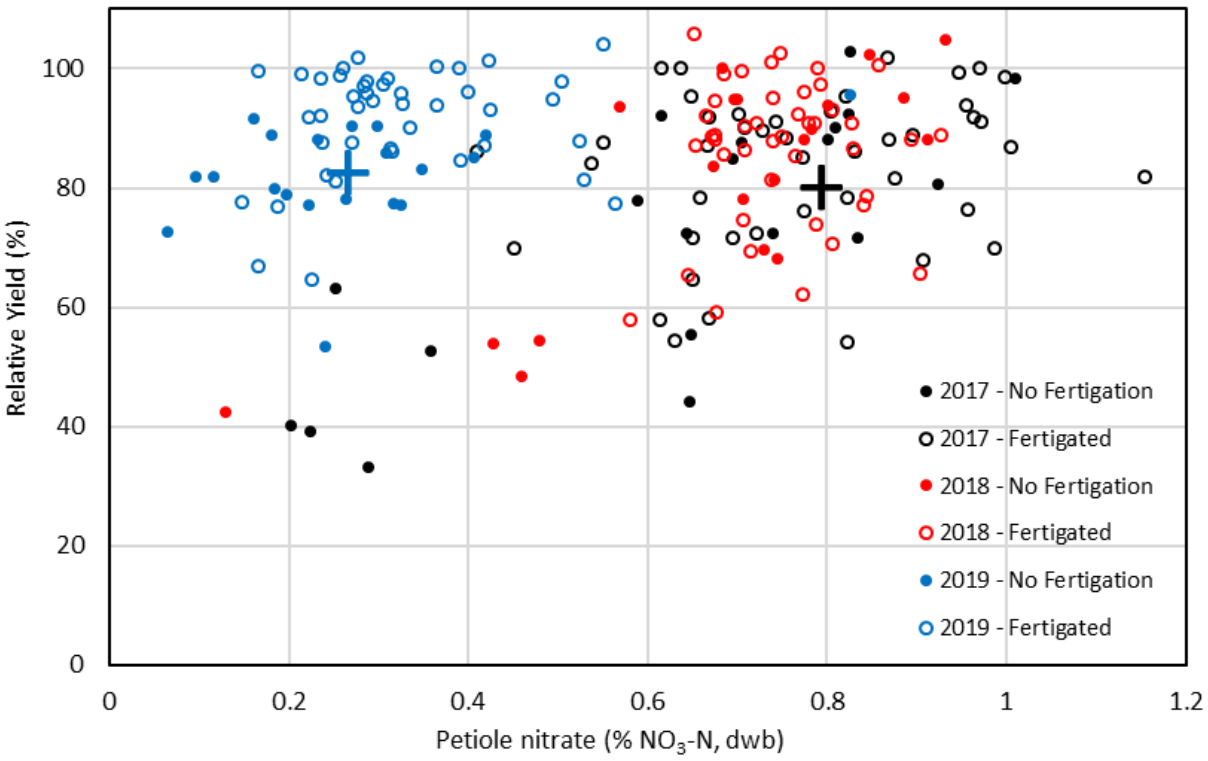


Figure 23. Relationship between early stem base nitrate concentration and relative yield of wheat.

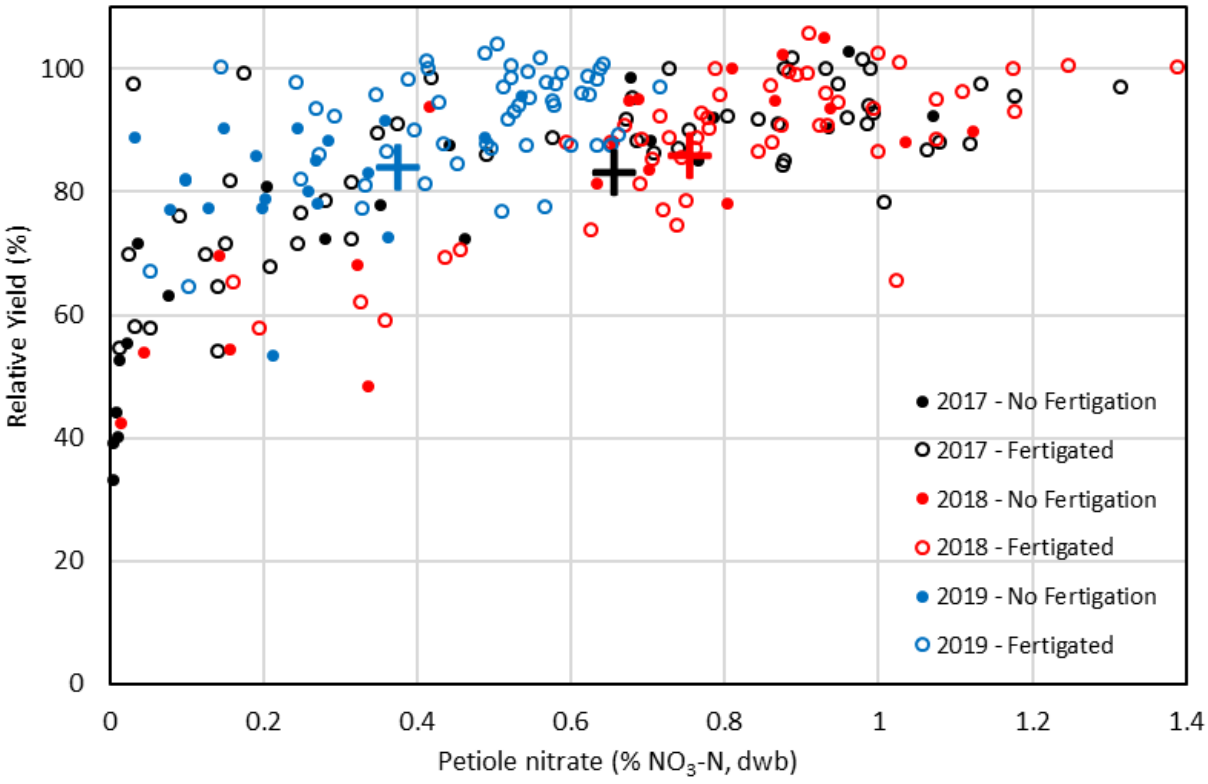


Figure 24. Relationship between late stem base nitrate concentration and relative yield of wheat.

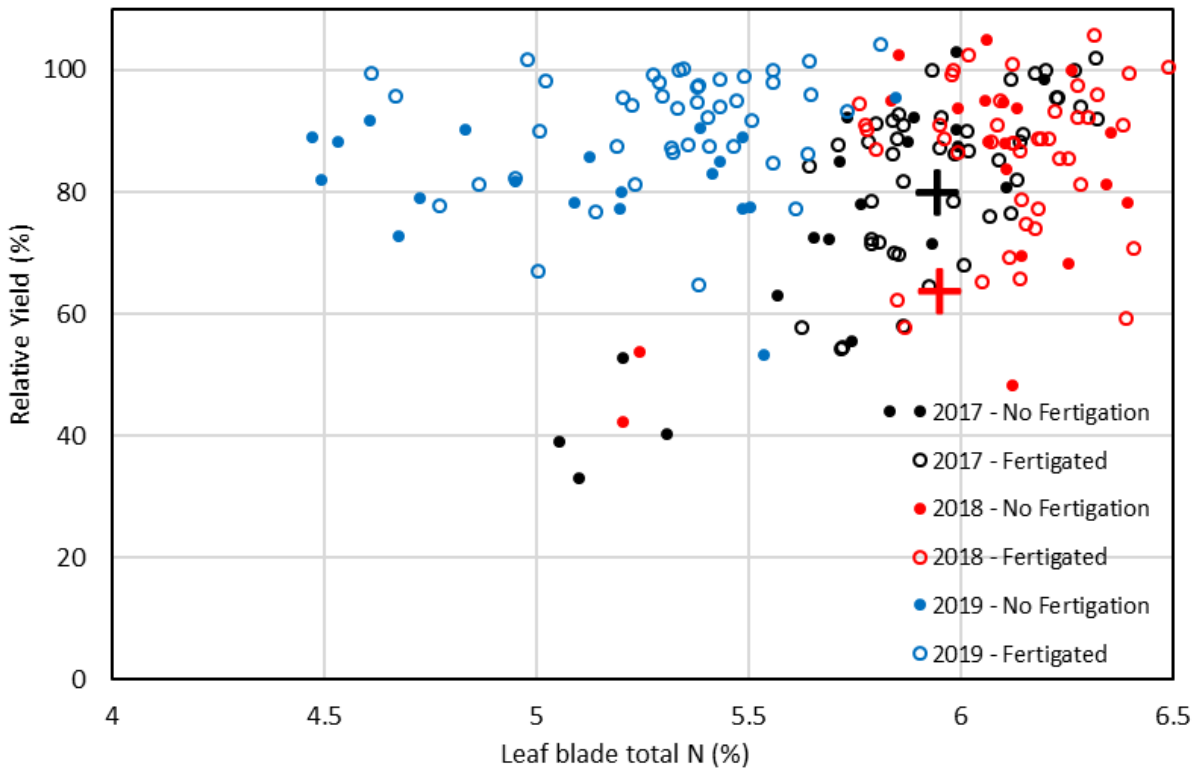


Figure 25. Relationship between early leaf blade total N concentration and relative yield of wheat.

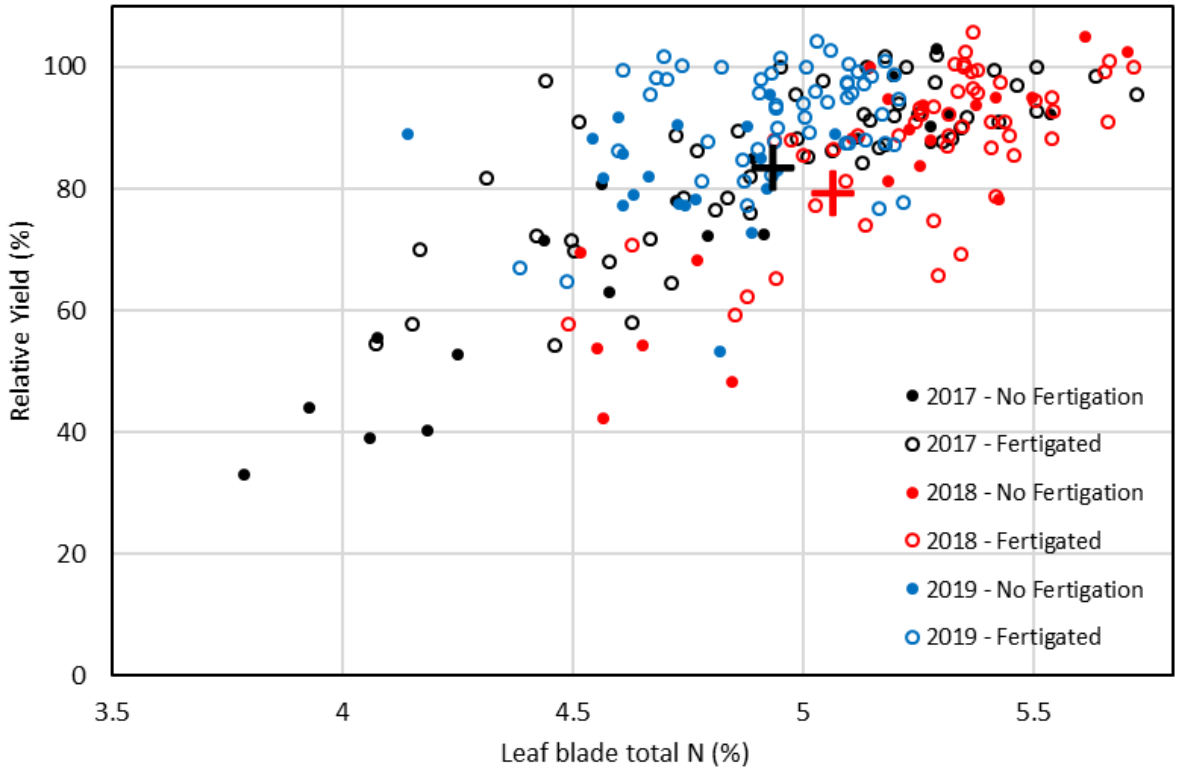


Figure 26. Relationship between late leaf blade total N concentration and relative yield of wheat.

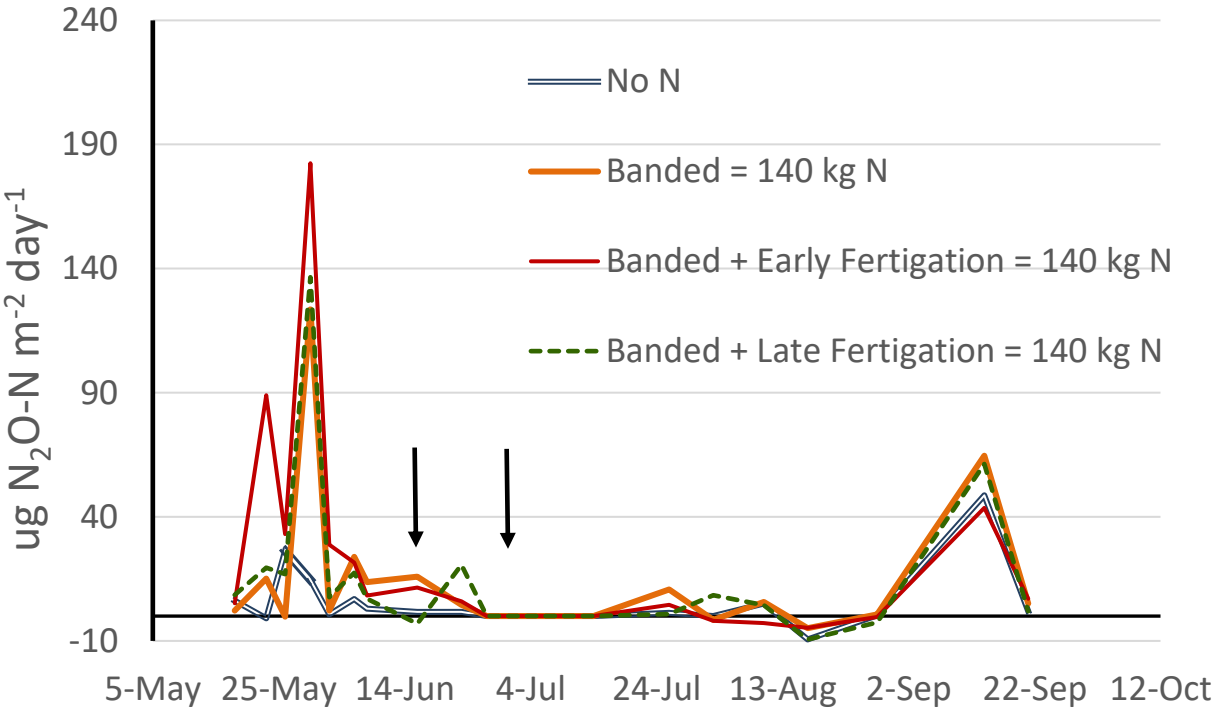


Figure 27. Daily flux patterns of three fertilizer application strategies and a check (no N) treatment at Outlook SK during the 2017 growing season. Arrows indicate fertigation events.

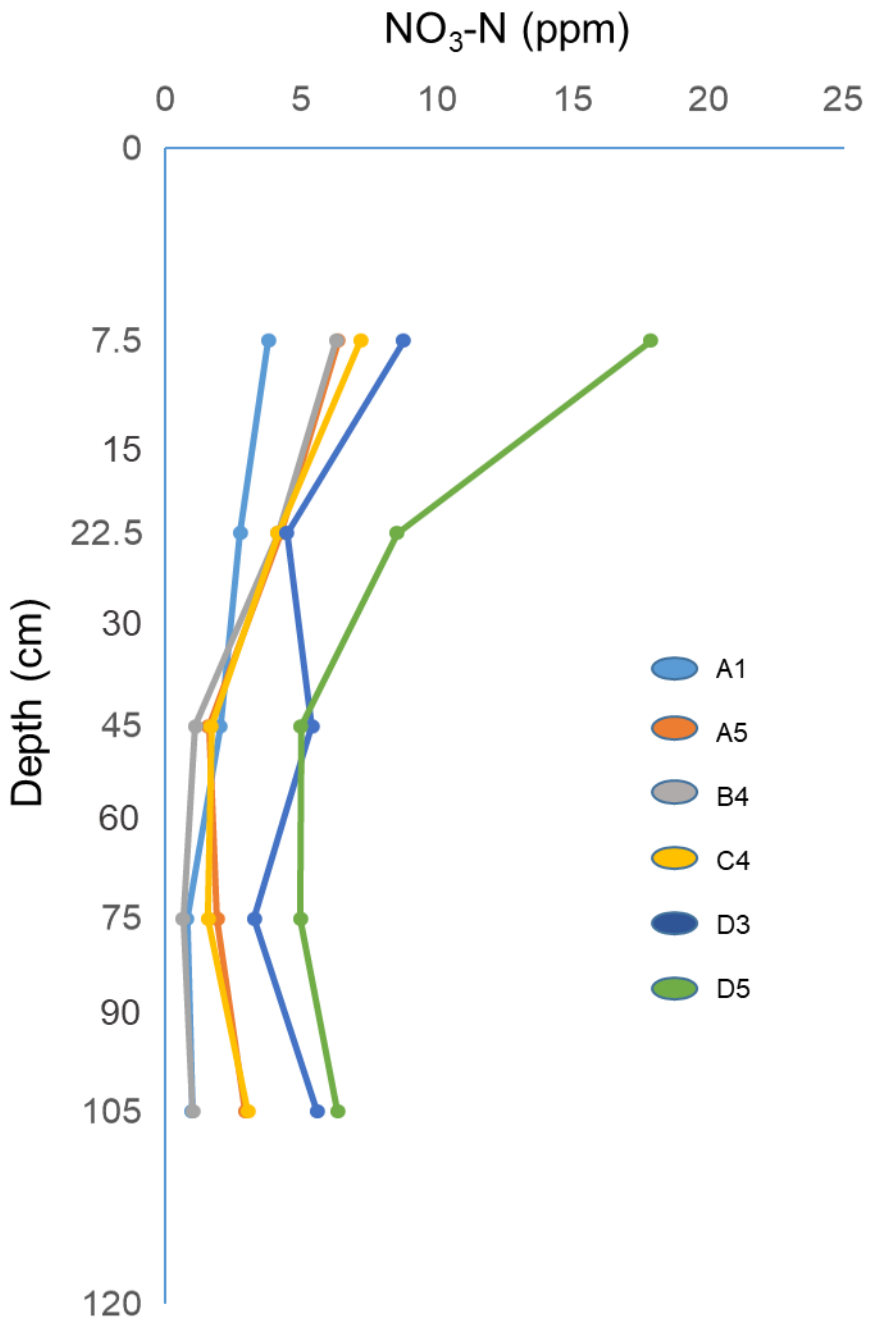


Figure 28. Soil profile nitrate-N concentrations (mg kg^{-1}) measured in the fall of 2017 on six fertilizer-N application strategies at Outlook, SK. A1 = No N; A5 = 140 kg N banded at seeding; B4 = Band + early fertigation (105 + 35 = 140 kg N); C4 = Band + late fertigation (105 + 35 = 140 kg N); D3 = Band + early + late fertigation (70 + 35 + 35 = 140 kg N); D5 = Band + early + late fertigation (140 + 35 + 35 = 210 kg N). Values are plotted at the midpoint of each depth increment measured (0-15, 15-30, 30-60, 60-90 and 69-120 cm), but represent the mean concentration for the entire increment.

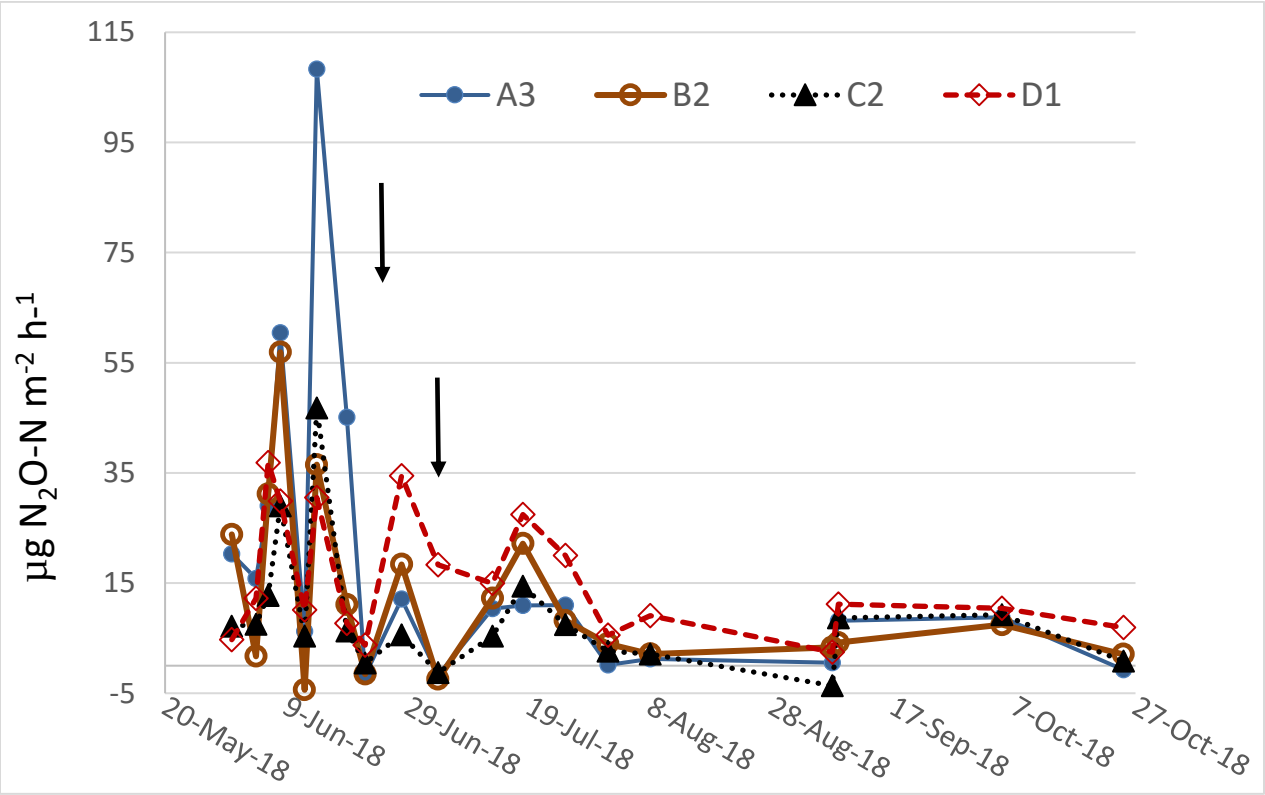


Figure 29. Mean daily flux patterns from four fertilizer management treatments at Outlook, SK during the 2018 growing season. A3 = 70 kg N banded at seeding (70+0+0); B2 = Band + early fertigation (35+35+0 = 70 kg N); C2 = Band + late fertigation (35+0+35 = 70 kg N); D1 = early + late fertigation (0 + 35 + 35 = 70 kg N). Arrows indicate fertigation events.

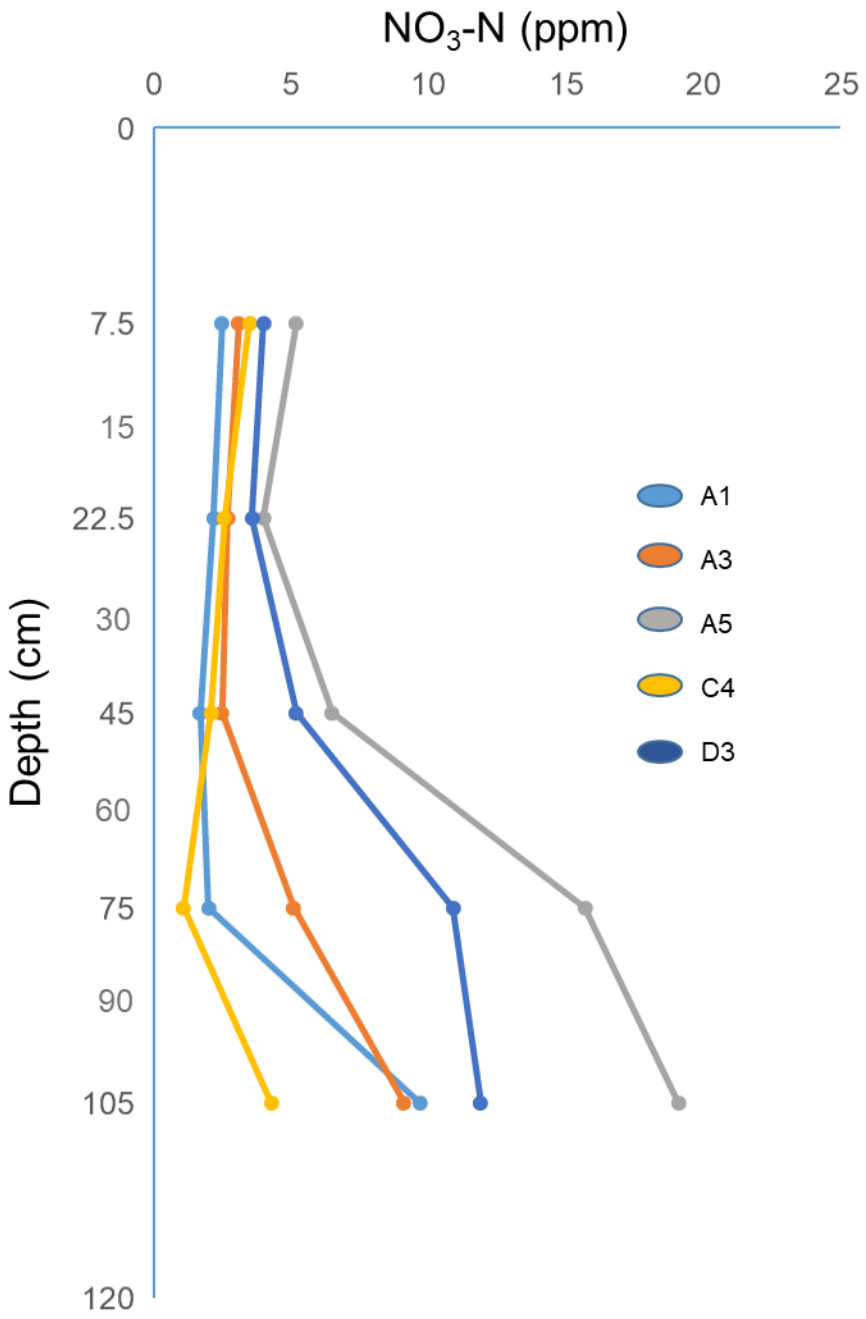


Figure 30. Soil profile nitrate-N (kg ha^{-1}) sampled in the fall of 2018 on five fertilizer-N application strategies at Outlook, SK. A1 = No N; A3 = 70 kg N banded at seeding; A5 = 140 kg N banded at seeding; C4 = Band + late fertigation (105 + 35 = 140 kg N); D3 = Band + early + late fertigation (70 + 35 + 35 = 140 kg N). Values are plotted at the midpoint of each depth increment measured (0-15, 15-30, 30-60, 60-90 and 69-120 cm), but represent the mean concentration for the entire increment.

Figure 31. Solution fertilizer injection apparatus (*Inject-O-Meter* piston pump).

Figure 32. Fertigating specific fertigation treatments of the wheat study on 27 June 2018. (You have to be up pretty early in the morning to beat the wind in Saskatchewan!)

Figure 33. Sampling the canola leaves (youngest fully expanded leaf, with petioles) on June 15 and June 28, 2017.

34. Cutting up and extracting sap from canola leaf petioles - June 15, 2017.

Figure 35. Strong N responses apparent in the wheat (left) and canola (right) studies on June 28, 2017.

Figure 36. Complete lodging of the wheat study on 24 September 2018 caused by the heavy snowfall three days earlier. The plots were nonetheless very successfully combined on October 5, after considerable work separating out the harvest rows (inset).

Figure 37. Principal investigator addresses tour at the study at CSIDC Annual Field day on July 13, 2017.

Appendix iii. Literature Cited

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