# Quantifying the Economic and Soil Quality Benefits of Long-Term No-Till using a Canola-Spring Wheat Rotation

CARP Project # 2012.4 – Component 3

Christiane Catellier[1], C. Holzapfel[1], B. May[2]

[1]Indian Head Agricultural Research Foundation, Indian Head, SK
[2]Agriculture & Agri-Food Canada, Indian Head, SK

ABSTRACT

Yields may improve with time spent under no-till management for many reasons, including enhanced SOM content and thus potential N mineralizability, and this effect is likely mediated by N fertility management. Producers are interested in knowing how to further enhance the productivity of no-till soils, and if soil and crop management approaches for soils that have been under no-till management for many years (long-term no-till) should differ from soils that were recently converted to no-till management (short-term no-till). Furthermore, it is desirable for producers to manage nutrient fertility efficiently, to sustain maximum crop productivity and profitability while minimizing wasteful nutrient application. In this study, we examined the cumulative and on-going changes occurring as length of time under no-till increases by comparing measures of crop productivity at two sites differing in the length of time under no-till. We determined the impact of a range of N fertility rates applied consecutively over a 10 year period, and how the response compared between long-term and short-term no-till. It was determined that early season plant N availability was higher in long-term than short-term no-till, and that plant available N in the early season also increased with past N application rates. By completing this project, we have gained a more in-depth understanding of the long-term impact of no-till combined with long-term N fertilizer management in crop production. The project will generate information on appropriate N fertilizer rates for maximizing productivity while reducing the impacts of N inputs on the environment.

# INTRODUCTION

The key to higher canola and other crop yields in the future is a soil with higher fertility or a greater ability to recycle nutrients. Recently published research showed that grain yields were 14% and 16% more for 22-31 years of no-till than 0-9 years of no-till in spring wheat and canola, respectively (see Lafond et al. 2011). Yields may improve with time spent under no-till because of increased levels and quality of soil organic matter (SOM), thus improved availability of nitrogen (N), phosphorus, and other nutrients, greater soil water-holding capacity, and better soil structure. Producers are interested in knowing how to further enhance the productivity of no-till soils, and if soil and crop management approaches for soils under no-till management for long periods of time (long-term no-till) should be the same for soils recently converted to no-till management (short-term no-till). Previous studies conducted on the Canadian Prairies focussing on the impact of no-till on soil quality or crop production have compared tillage based systems to no-till systems. In this study, we examine how soil quality and production can continually improve in no-till systems by comparing the length of time under no-till. It is a very unique situation due to the adjacent fields being used with the desired contrasting no-till history (up to 31 years no-till). This allows us to determine the cumulative and on-going changes occurring as length of time under no-till increases, and the time frame that we can expect improvements from no-till. Soil improvement will be quantified with measurements of grain yield, grain N, and flag leaf N responses of canola and spring wheat to different rates of N fertilizer.

Supplying sufficient N to meet crop requirements for optimum yield depends on the available (residual) inorganic N in the soil, coupled with presumed or predicted N mineralization during the growing season, with the remainder provided through fertilizer additions. The cycling of soil organic N and potential N mineralizability, as measured by higher N uptake in grain, is enhanced in no-till soils as it is closely related to SOM content. The greatest source of SOM is the residue contributed by crops, thus proper management and fertilization producing high yields will increase the quantity of residue and SOM sequestered in the soil. When no-till systems are initiated, surface SOM increases rapidly, increasing the N immobilization potential. During these first years, N management is critical to minimize potential crop-N deficiency. With longer periods under no-till management, the SOM may attain a new equilibrium level, and N mineralization may increase, resulting in lower N requirements. The length of time required under no-till to attain this level, or the “soil building” period, is not known and has important implications for efficient N fertility management in no-till systems.

Thus, the length of time under no-till management will likely influence N dynamics, but the effect will be mediated by N fertility management over the long term. Using higher rates of N fertilizer (exceeding what is removed in the grain) may accelerate the building of soil productivity, if the soil is capable of absorbing and sequestering the N into stable forms that are less conducive to losses. Nitrate ($NO_3^-$) accumulation occurs when N rate exceeds that required for optimum yield, and the soil fails to transform the excess N into more stable forms. The rate of applied N that can accelerate and contribute to soil building without resulting in nitrate accumulation and losses to the environment may change as the length of time under no-till management increases. We need to better understand soil building and if adding more N than what is removed is one way to improve soils more quickly without necessarily increasing environmental risks, and to determine if soil-building by using higher N rates is apparent in both long-term and short-term no-till soils.

By completing this project, we will have gained a more in-depth understanding of the long-term impact of no-till combined with long-term N fertilizer management on soil quality and crop production. The project will generate information on appropriate N fertilizer rates for maximizing productivity while reducing the impacts of N inputs on the environment. Crop yields are intrinsically tied to soil health and understanding the changes in soil quality that occur as a consequence of no-till continuous cropping practices will contribute to a greater understanding of how production practices impact the soil and subsequent crop yields.

## METHODS

### *Site description*

The research site consisting of two adjacent fields with contrasting land management histories, long-term (LT) no-till and short-term (ST) no-till, is located approximately 19 km south-east of Indian Head, Saskatchewan (50.32° North 103.58° West). The soil type for both fields is an Oxbow Loam (Orthic Black Chernozem or Typic Haplocryoll) situated in the thin Black soil zone with a climate that is considered sub-humid continental. A summary of weather information for the 2012-2014 growing seasons and long-term normal is provided in

Table 1.

Table 1. Weather data for the 2012-2014 seasons, along with long-term normals (1981-2010) at Indian Head.

| Year | May | June | July | August | Growing season |
|---|---|---|---|---|---|
| | ---------------------------- Mean Temperature (°C) ---------------------------- | | | | |
| 2012 | 9.9 | 16.5 | 19.2 | 17.1 | 15.7 |
| 2013 | 11.9 | 15.3 | 16.3 | 17.1 | 15.2 |
| 2014 | 10.2 | 14.4 | 17.3 | 17.4 | 14.8 |
| Long-term | 10.8 | 15.8 | 18.2 | 17.4 | 15.6 |
| | ------------------------------ Precipitation (mm) ------------------------------ | | | | |
| 2012 | 79 | 51 | 125 | 30 | 285 |
| 2013 | 17.1 | 103.8 | 50.4 | 6.1 | 177 |
| 2014 | 36.0 | 199.2 | 7.8 | 142.2 | 385 |
| Long-term | 51.8 | 77.4 | 63.8 | 51.2 | 244 |

### *Experimental design*

The present study is an extension of an on-going study, initiated in 2002, comparing long-term and short-term no-till in which five rates of nitrogen (0, 30, 60, 90, and 120 kg N $ha^{-1}$) and two methods of phosphorus fertilizer placement (seed-placed or side-banded) **were applied repeatedly on the same plots over a period of 10 years** (2002-2011) in order to capture the long-term, cumulative effects of the experimental treatments. Each combination of treatments (5 N rates x 2 P placement = 10 treatments total) was established on the adjacent long-term and short-term no-till fields, and the experiment was set up as a factorial randomized complete block design with three replicates in each of the two fields. Thus, the study was structured in such a way that each of the five N fertilizer rates was present twice in each replicate. It was determined in the previous study that P fertilizer placement did not affect crop yields in the long-term, thus previous P placement treatments could be disregarded in the experimental design of the present study. In the present study, the same long-term N rate treatments were applied to one set of the five N fertility rate treatments while a uniform N rate (80 kg N ha$^{-1}$) was applied to the other set to determine if long-term, past N management has an effect on soil productivity. The treatments are outlined in

Table 2.

Table 2. Summary of treatments which were arranged randomly and replicated three times in each of the LT and ST no-till fields. Treatments 1-5 are referred to in the results as “variable N rate” treatments while treatments 6-10 are referred to as “constant N rate” treatments.

| Treatment no. | Rate type | Past N rate (kg N ha$^{-1}$) | Applied N rate (kg N ha$^{-1}$) |
|---|---|---|---|
| 1 | Variable | 0 | 0 |
| 2 | Variable | 30 | 30 |
| 3 | Variable | 60 | 60 |
| 4 | Variable | 90 | 90 |
| 5 | Variable | 120 | 120 |
| 6 | Constant | 0 | 80 |
| 7 | Constant | 30 | 80 |
| 8 | Constant | 60 | 80 |
| 9 | Constant | 90 | 80 |
| 10 | Constant | 120 | 80 |

Land management (no-till) history was not replicated in this study – there was only one long-term no-till field and one short-term no-till field. Thus, it is possible that differences in soil productivity, as measured in our study, could be a result of inherent differences in the two fields. However, previous research has shown that given the proximity of the two fields, other factors that play important roles in soil productivity, including soil texture, environmental factors, and the interaction of weather and soil physical properties, can be assumed to be identical. Previous fertility management also plays a role in soil productivity; however, this factor is accounted for as it is included in the experimental design of the study.

### *Agronomic information and data collection*

Soil samples were collected from each plot in both the LT no-till field and the ST no-till field in the fall of 2011 and 2013. Samples were collected using a 0-15 cm and 15-60 cm depth increment. The soil samples were air-dried immediately, ground and sieved to <2 mm aggregates and stored until analyzed for $NaHCO_3$ extractable $NO_3$-N and $PO_4$-P. The ppm concentrations of $NO_3$-N and $PO_4$-P were converted to kg $ha^{-1}$ using a factor of 1.8 for the 0-15 cm depth and 6 for the 15-60 cm depth. Total residual $NO_3$-N and $PO_4$-P (kg $ha^{-1}$) were calculated for the entire soil profile in each plot. Soil samples were not obtained in the fall of 2012 so residual nutrients for the 2013 growing season (canola rotation) are unknown.

Spring wheat was seeded in each plot in the spring of 2012 and 2014, and canola was seeded in 2013. All plots were seeded using a Conserva-Pak plot drill with 12 openers spaced 31 cm apart and all fertilizer was side-banded at 2.5 cm to the side and 7.5 cm below the seed row. Nitrogen fertilizer (46-0-0) was applied to obtain the rates specified in the protocol, while ammonium phosphate (11-52-0) was applied at 35 kg $P_2O_5$ $ha^{-1}$. In the canola year only, potassium sulfate (0-0-52-17) was applied before seeding using a broadcast application at the equivalent amount of 20 kg S $ha^{-1}$. Crop protection products were applied as needed to maintain weeds and pests at non-limiting levels.

Spring plant density was determined for both spring wheat and canola by counting the number of plants in two separate 1-metre sections of crop row per plot and the value was reported as plants $m^{-2}$. Flag leaf nitrogen concentration was determined for the spring wheat phase only. Flag leaves were collected randomly on the full length of the plots near the centre of each plot after full heading. Enough leaves were collected so that ~25 grams of dry leaf material was obtained. Immediately after collection, the leaves were dried at $40^{o}C$ and then ground to <1 mm. A sub-sample of the ground flag leaf tissue was analyzed for N using the Kjeldahl digestion method. Flag leaf N is expressed as a percent. Grain yields were determined by mechanically harvesting the entire plot at maturity and weighing the grain. Grain yields were corrected to 14% grain moisture for spring wheat and 10% moisture for canola. Results are reported as kg $ha^{-1}$. Grain N was determined for both spring wheat and canola by the Kjeldahl digestion method. The percent N was multiplied by grain yield to estimate the amount of N removed in the grain in kg $ha^{-1}$.

### *Statistical analysis*

The analysis of the data was conducted under the assumption that differences between the land management effects were due to long-term tillage management differences rather than inherent differences in soil properties and climatic conditions (See *experimental design*). The analysis was conducted separately for each crop type (spring wheat and canola), with variable rate plots (treatments 1-5) and constant rate plots (treatments 6-10) either together or separate depending on which response variable was being tested. Linear regression models (ANCOVA) were used to determine whether the N rate response curves of each of the response variables were either linear or quadratic, whether they differed significantly between no-till histories or between constant and variable rate plots when appropriate, using the 'lm' function in R. Different N rate explanatory variables were used (Applied N, Past N, or Total N (residual $NO_3$-N + applied N)), depending on which response variable was being modelled. A mixed model was used when both wheat years were analyzed together, with year as a random effect only, using the 'lme' function in R. The explanatory variables in the initial ANCOVA models included different combinations of the factor History (levels ST or LT), the factor Rate Type (levels constant or variable), and their interaction with each other and with the linear and quadratic N rate variable. The least significant interactions and variables were removed from the model one at a time and permanently excluded as long as their removal did not result in a significantly inferior model fit relative to the previous model ($P<0.05$). The reduced final model did not have inferior model fit relative to the initial model ($P<0.5$). Removal of non-significant variables was used to improve model fit and identify the most influential variables.

## RESULTS AND DISCUSSION

### Plant density

The initial linear models for plant density included the factors History, Applied N rate, and their interaction. Constant and Variable rate plots were both included but the explanatory variables Rate Type and the quadratic N rate were not included.

#### *i. Canola*

The final model included History ($P=0.120$), Applied N ($P=0.026$), and their interaction ($P=0.033$). ST plots had a higher intercept but slightly negative response to Applied N, while LT plots had a lower intercept but positive response to Applied N (Figure 1). Average plant density was within the recommended range of 70-140 plants per square metre.

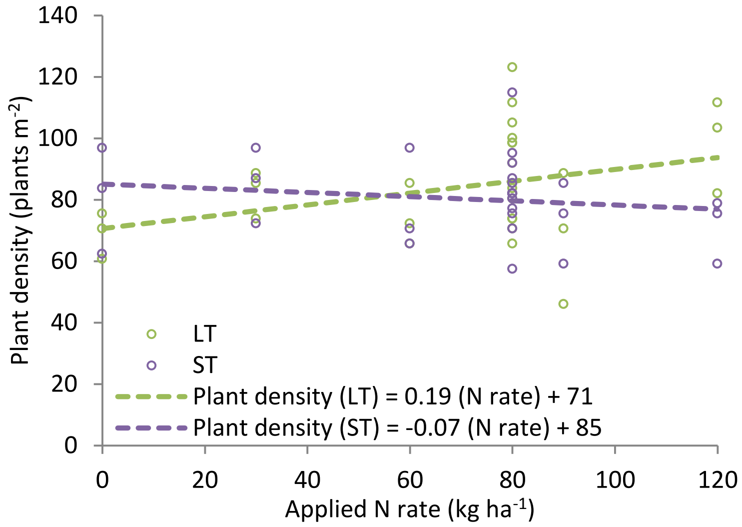

Figure 1. The effect of applied N rate and no-till history on canola plant density at Indian Head in 2013.

#### *ii. Wheat*

Both years were combined in a mixed model analysis, and the final model indicated that plant density had a negative linear response to Applied N (P=0.043), and ST plots had a slightly lower plant density than LT plots (P=0.037) (Figure 2). Average plant density was not reduced to a level that was lower than recommended (215-270 plants $m^{-2}$), though values in 2014 appeared to be lower than in 2012.

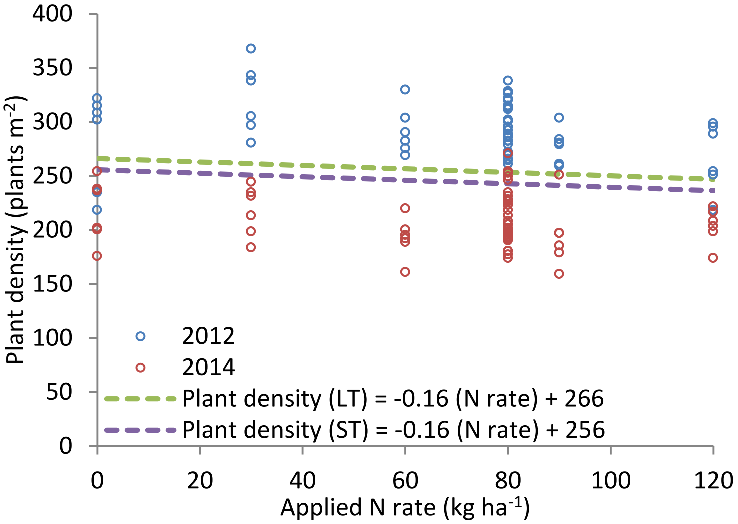

Figure 2. The effect of applied N rate and no-till history on wheat plant density at Indian Head in 2012 and 2014 combined.

## Flag Leaf N – Wheat only

Both years of wheat yield data were combined in a mixed model analysis with year as a random factor only. Variable and constant rate plots were analyzed separately to simplify interpretation of the results. The initial linear models for flag leaf N included the factor History and its interaction with the linear and quadratic N rate variables (either Applied N or Past N).

The final model for Flag leaf N in **variable** N rate plots indicated an interaction between the quadratic N rate variable and History (P=0.019), thus a different quadratic relationship with Applied N for each LT and ST no-till (Figure 3). LT no-till plots had a positive quadratic relationship with Applied N, and a higher overall N content at all levels of applied N, while ST no-till plots had a negative quadratic relationship with applied N and a lower overall N content. The response to Total N was nearly identical and is not shown. Results from the variable rate plots indicate that no matter the current or past fertility level, LT no-till has a greater ability to provide plant-available N during the growing season, especially at the lowest and highest N fertility rates.

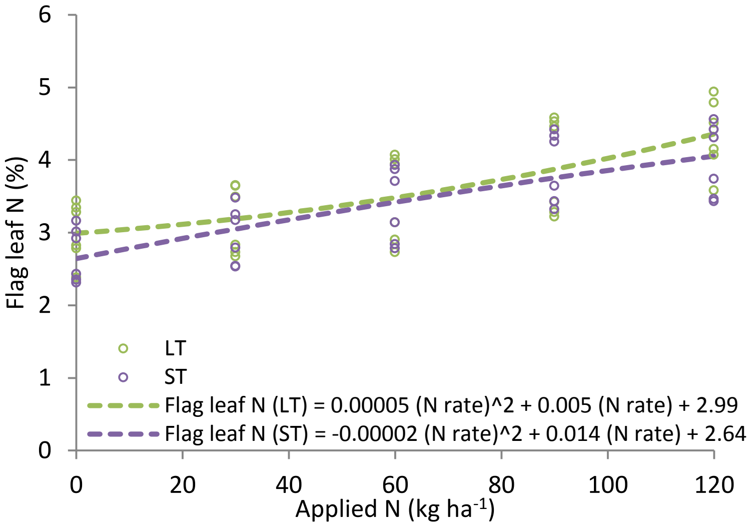

Figure 3. The effect of applied N and no-till history on wheat flag leaf N in **variable** rate plots at Indian Head in 2012 and 2014 combined.

The final model for the response of flag leaf N to Past N in **constant** N rate plots showed a linear increase with past N (P<0.001) and a different intercept for the two no-till histories (P<0.001) but no interaction between the two variables (Figure 4). This again indicates that LT no-till has a greater ability to provide plant-available N during the growing season, at any current or past N fertility level. In addition, as there was a linear increase with past N even though applied rates were constant, this indicates that N mineralization increased with past N rates in both ST and LT no-till fields.

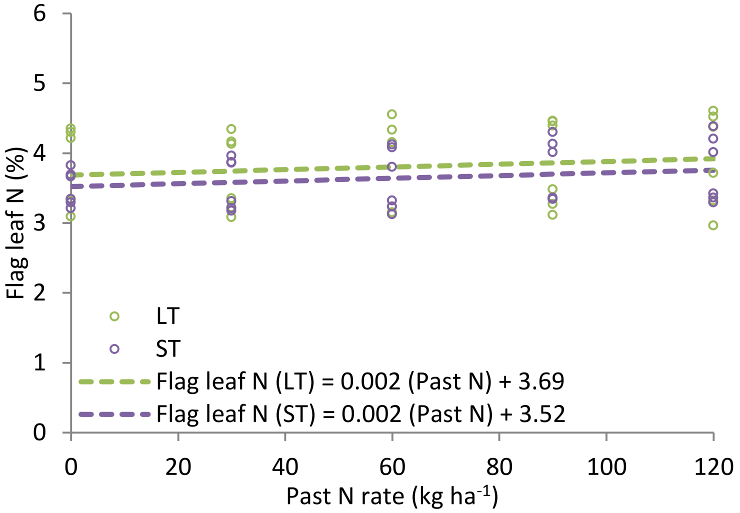

Figure 4. The effect of past N rate and no-till history on wheat flag leaf N in **constant** rate plots at Indian Head in 2012 and 2014 combined.

## Yield

### *i. Canola*

Constant and variable rate plots were analyzed together for canola yield. The initial linear models for canola yield included the factors History, Rate Type, and their interactions with each other and with the linear and quadratic N rate variable (Past N, which is equivalent to Applied N for the variable rate plots).

The final model for the yield response to Past N in combined **variable and constant** N rate plots indicated a significant interaction between Rate type and Past N ($P<0.001$), thus different linear response to past N for the variable and constant rate plots. Variable rate plots had a strong positive linear response to Past N (note that Past N is equivalent to Applied N in variable N rate plots), while constant rate plots had a near-0 response to Past N. There was no difference between no-till histories (Figure 5). The same responses to N rate were detected when variable and constant rate plots were analyzed separately (positive linear response to applied N in variable rate plots and no significant response to past N in constant rate plots – data not shown).

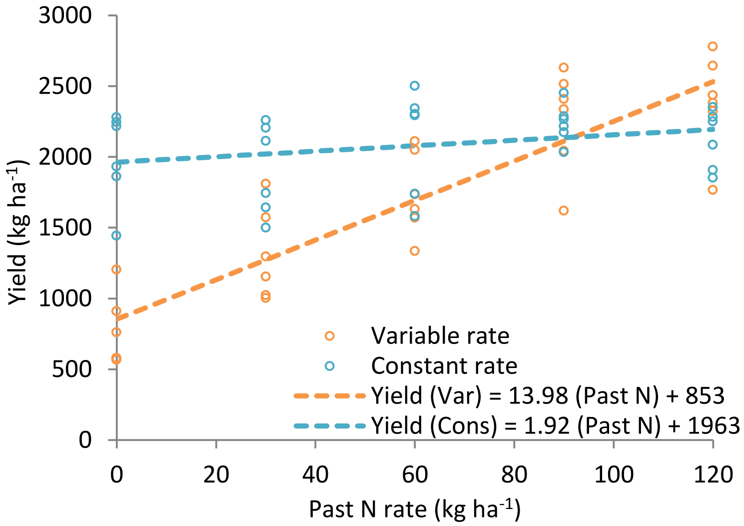

Figure 5. The effect of past N rate on canola yield in variable and constant rate plots at Indian Head in 2013. Past N rate is equivalent to applied N rate in variable rate plots.

### ii. *Wheat*

Both years of wheat yield data were combined in a mixed model analysis. Constant and variable rate plots were analyzed together. The initial linear model for wheat yield included the factors History, Rate Type, and their interactions with each other and with the linear and quadratic N rate variable (Past N or Total N).

The final model for the wheat yield response to Past N in combined **variable and constant** N rate plots indicated a significant interaction between Rate type and Past N ($P<0.001$), thus different linear response to Past N for the variable and constant rate plots. Similar to canola yield response, variable rate plots had a strong positive linear response to Past N (note that Past N is equivalent to Applied N in variable N rate plots), while constant rate plots had a near-0 response to Past N. There was no difference between no-till histories (Figure 6). The same responses to N rate were detected when variable and constant rate plots were analyzed separately (positive linear response to applied N in variable rate plots and no response to past N in constant rate plots - data not shown).

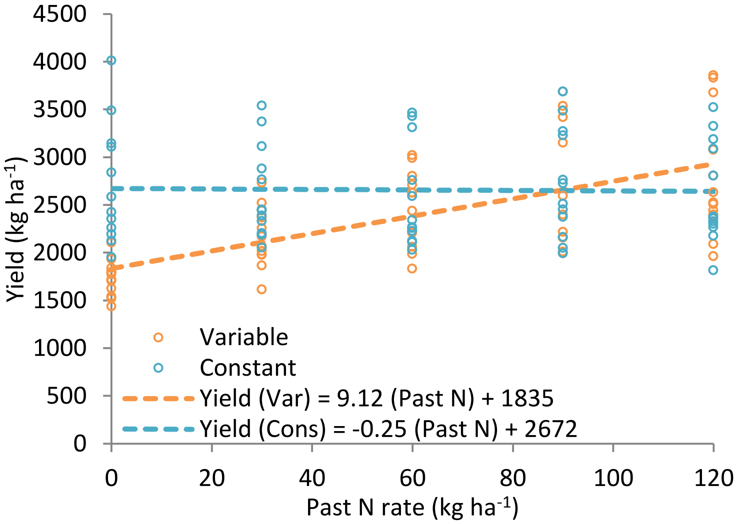

Figure 6. The effect of past N rate on wheat yield in **variable and constant** rate plots at Indian Head in 2012 and 2014 combined. Past N is equivalent to applied N in variable rate plots.

Conversely, the final model for the wheat yield response to Total N in combined **variable and constant** N rate plots indicated a quadratic response to Total N ($P<0.001$), but no effect of Rate type or History (Figure 7). The different response of yield to N rate (linear) and Total N (quadratic) suggests that yields are responding to both applied and residual N, but that there is a diminishing return for residual N at the higher rates of past N application. Thus, the highest applied N rate of 120 kg N ha$^{-1}$ is approaching the optimal N rate for wheat, as any amount of available N beyond what was applied did not result in a linear increase in yield.

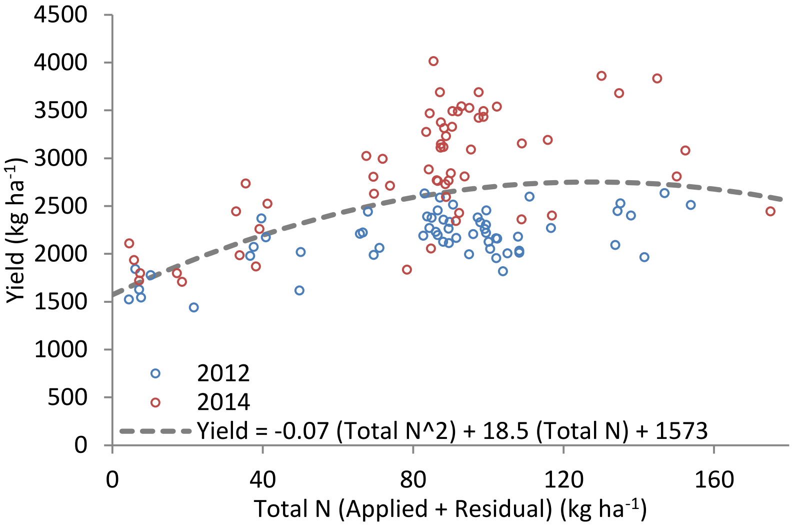

Figure 7. The effect of total N (applied + residual) on wheat yield in **variable and constant** rate plots at Indian Head in 2012 and 2014 combined.

## Grain N

### *i. Canola*

Constant and variable rate plots were analyzed together for canola grain N. The initial linear models for canola grain N included the factors History, Rate Type, and their interactions with each other and with the linear and quadratic N rate variable (Past N, which is equivalent to Applied N for the variable rate plots).

The grain N response in canola was very similar to the yield response. The final model for the effect of Past N on grain N in canola indicated a significant interaction between Rate type and Past N ($P<0.001$), thus different linear response to Past N for the variable and constant rate plots. Variable rate plots had a strong positive linear response to Past N (note that Past N is equivalent to Applied N in variable N rate plots), while constant rate plots had a near-0 response to Past N. There was no difference between no-till histories (Figure 8). The same responses to N rate were detected when variable and constant rate plots were analyzed separately (positive linear response to applied N in variable rate plots and no response to past N in constant rate plots - data not shown).

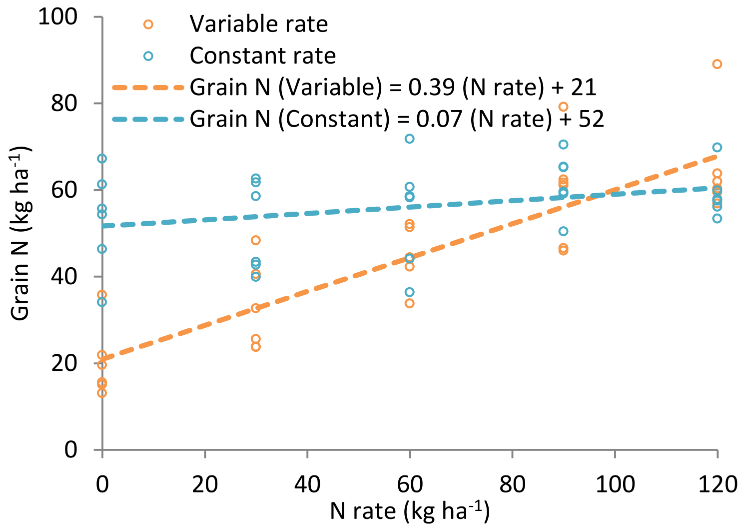

Figure 8. The effect of past N rate on canola grain N content in variable and constant rate plots at Indian Head in 2013. Past N is equivalent to applied N in variable rate plots.

### *ii. Wheat*

Both years of wheat grain N data were combined in a mixed model analysis. Constant and variable rate plots were analyzed together. The initial linear model for wheat grain N content included the factors History, Rate Type, and their interactions with each other and with the linear and quadratic N rate variable (Past N, which is equivalent to applied N in variable rate plots).

The grain N response in wheat was also very similar to the yield response. As with canola, the final model for the effect of Past N on grain N in wheat indicated a significant interaction between Rate type and Past N ($P<0.001$), thus different linear response to Past N for the variable and constant rate plots. Again, variable rate plots had a strong positive linear response to Past N (Past N is equivalent to Applied N in variable N rate plots), while constant rate plots had a near-0 response to Past N. There was no difference between no-till histories (Figure 9). The same responses to N rate were detected when variable and constant rate plots were analyzed separately (positive linear response to applied N in variable rate plots and no significant response to past N in constant rate plots - data not shown). There was also a linear response with Total N as the N rate variable; however, there was no difference between constant and variable rate types (data not shown).

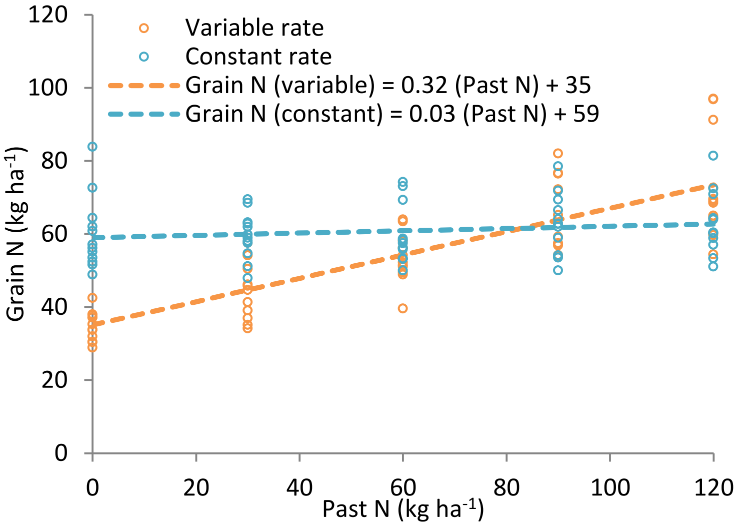

Figure 9. The effect of past N rate on wheat grain N content in variable and constant rate plots at Indian Head in 2012 and 2014 combined. Past N is equivalent to applied N in variable rate plots.

## Residual nutrients

### i. *2011*

Soil samples from fall 2011 were obtained prior to the initiation of the constant N rate treatments, thus can be used to illustrate the accumulation of nutrients at varying levels of applied N over the long term (10 years). The initial models for residual $NO_3$-N and $PO_4$-P in the 0-24” soil depth included the factor History and its interaction with the linear and quadratic N rate variable (Past N).

A significant outlier was removed from the residual $NO_3$-N data in 2011 (>50 kg N $ha^{-1}$ at the 30 kg N $ha^{-1}$ rate). Subsequently, the final model for residual $NO_3$-N indicated a similar positive quadratic response to Past N for both no-till histories ($P=0.003$; interaction not significant), but a different intercept for each of the no-till histories ($P<0.001$; Figure 10). The response suggests that residual $NO_3$-N is higher in LT than in ST no-till, at all levels of applied N, and it appears as though significant accumulation occurs beyond the 90 kg $ha^{-1}$ applied rate in both LT and ST no-till.

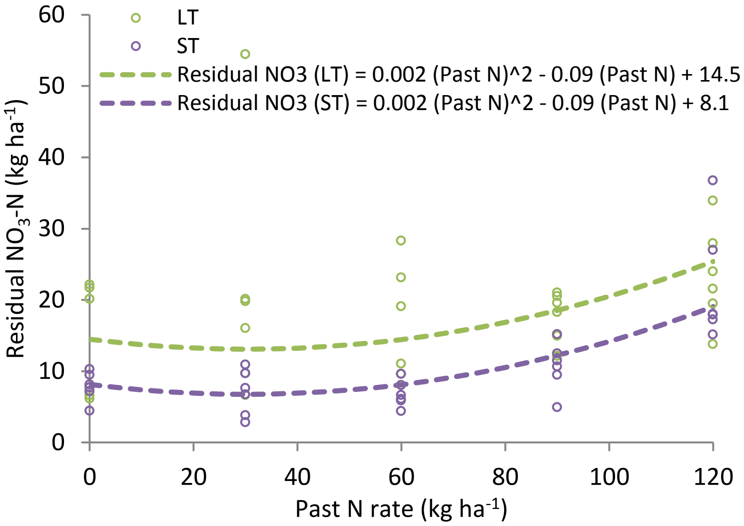

Figure 10. Accumulation of $NO_3$-N in LT and ST no-till after 10 years of varying applied N rates.

The final model for residual $PO_4$-P indicated a similar negative linear response to Past N for both no-till histories (P<0.001; interaction not significant), but again, a higher intercept for LT (P<0.001; Figure 11). The response suggests that residual $PO_4$-P is higher in LT than in ST no-till, at all levels of applied N, and it appears as though $PO_4$ is depleted over time at the higher rates of applied N. This is likely a result of greater crop yields which would remove more soil nutrients at the higher N application rates.

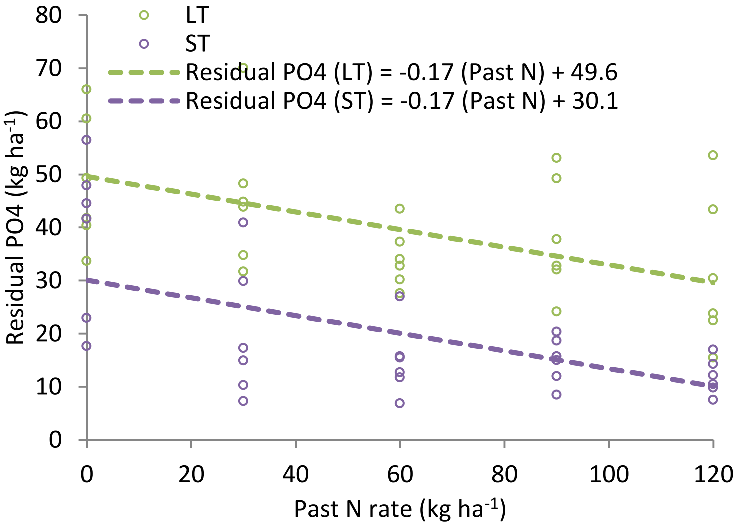

Figure 11. Accumulation of $PO_4$-P in LT and ST no-till after 10 years of varying applied N rates.

### ii. *2013*

Soil samples were collected again in fall 2013, after two seasons of applying the constant N rate to half of the Past N rate treatments. The initial models for residual $NO_3$-N and $PO_4$-P in the 0-24" soil depth included the factor History and its interaction with the linear and quadratic N rate variable (Past N).

In contrast to what was seen in 2011, the response to past N rates was quadratic, and there was an interaction between no-till history and past N rate, indicating a different response for LT and ST no-till fields (Figure 12). The same response to past N and history was observed when constant and variable rate plots were analyzed separately.

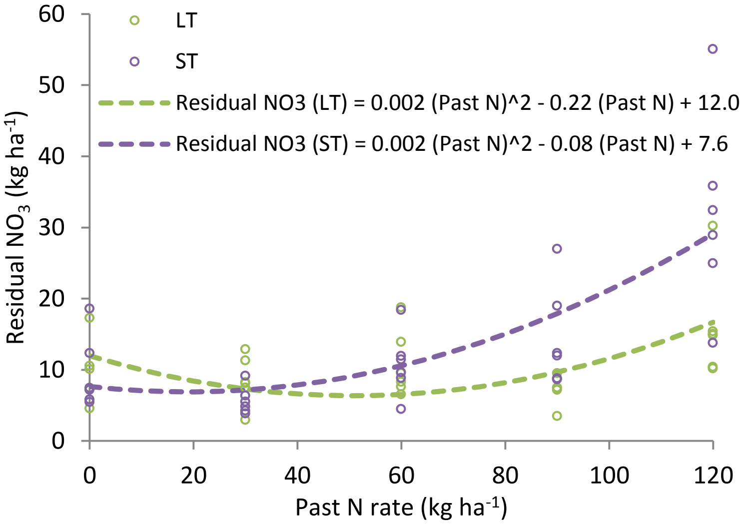

Figure 12. Accumulation of NO$_3$-N in LT and ST no-till in 2013.

The final model for residual PO$_4$-P in 2013 indicated the same negative linear response to Past N for both no-till histories (no interaction), but again, a higher intercept for LT (Figure 13). The same response to past N and history was observed when constant and variable rate plots were analyzed separately.

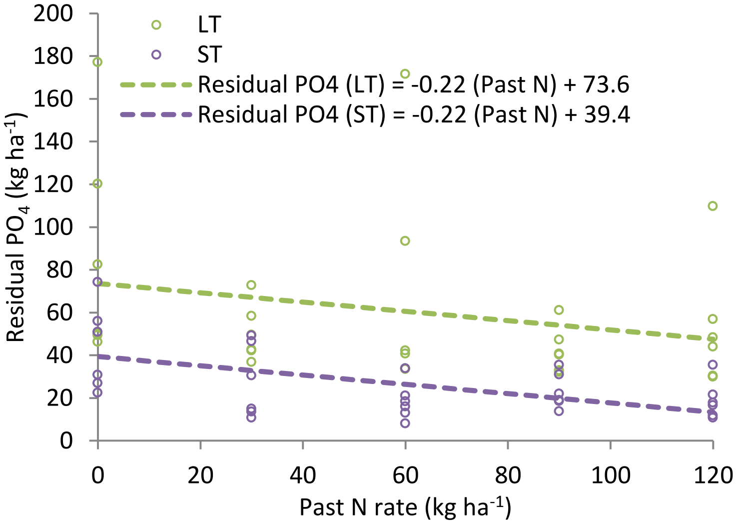

Figure 13. Accumulation of PO$_4$-P in LT and ST no-till in 2013.

# GENERAL DISCUSSION AND CONCLUSIONS

In this study, soil improvement in ST compared to LT no-till managed soils was quantified with measurements of flag leaf N, grain yield, and grain N responses of canola and spring wheat to different rates of N fertilizer. The constant N rate treatment was implemented to determine the influence of past N fertility management, and how it differs between the two no-till histories.

Most interesting was the wheat flag leaf N response. In both variable and constant rate plots, flag leaf N was higher overall in LT no-till plots than in ST no-till plots. This indicates that at any rate of applied N, LT no-till soils have a greater ability than ST no-till soils to provide early growing season N requirements. Thus, ST no-till fields would require a higher rate of applied N to maintain an equivalent level of N uptake in the crop in the early growing season. In addition, there was a significant linear increase in flag leaf N with past N rate in plots with a constant applied N rate of 80 kg N $ha^{-1}$. This indicates that early growing season N availability increased with past N rates, though it is not certain whether this was from higher residual N or through greater N mineralization. However, the linear response to past N was the same for both no-till histories, thus, even with higher overall flag leaf N in LT than in ST no-till, this indicates that fertility management for the purposes of soil building should not differ between LT and ST no-till soils. Furthermore, the highest rate of applied N, 120 kg N $ha^{-1}$, did not appear to be excessive for soil building purposes in either of the no-till histories, as the flag leaf N response was linear and not quadratic, which would otherwise indicate diminishing returns at the higher rate of applied N.

In contrast to past results, yields of either canola or spring wheat did not differ between LT and ST no-till fields. There was no response to past N in constant rate plots in either canola or spring wheat, and there was a linear response to applied N in variable rate plots, as expected. It is possible that after more than 10 years of no-till management, soil quality in ST no-till fields is approaching that found in LT no-till fields. There is likely still some difference in soil nutrient cycling abilities, as explained by the difference in flag leaf N response between the two fields. However, it is likely that later in the growing season, factors other than soil quality become more limiting to yield in both LT and ST no-till fields equally. The grain N response in both canola and grain N paralleled the yield response and further emphasizes this point.

Residual nutrients are generally higher in LT than ST no-till, other than with $NO_3$-N in 2013, where nitrate accumulation occurred at the higher rates of applied N in the ST no-till plots. Nitrate accumulation was less severe in LT than ST no-till at the highest applied N rates in both years. Residual nutrients may be higher in LT than ST no-till because the overall fertility is higher, and cycling through different phases more quickly, with N and P in various forms and bound more tightly to the soil and less conducive to loss. As there were no differences in yield or grain N between the two no-till histories, it is not likely that nutrients were being taken up more readily in ST compared to LT plots, which would have led to the lower residual levels in ST no-till. The results also demonstrate the importance of balanced fertility management, as $PO_4$-P accumulation in plots with low past and current N fertility rates.

By completing this project, we have gained a more in-depth understanding of the long-term impact of no-till combined with long-term N fertilizer management on crop production. Additional research is needed in fertilizer management because proper access to nutrients by the plant is essential for crop growth and fertilizers remain a key component to long-term soil quality and productivity.

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