Impact of long- and short-term no-till on the soil organic N pool and soil N dynamics

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Abbreviations: LTNT: long-term no-till; and STNT: short-term no-till

Short title: Soil N dynamic with no-till

ABSTRACT

Understanding nitrogen (N) fertilizer requirement for soils under varied lengths of no-till could have practical implications regarding optimal N fertilizer requirements. This study examined the soil organic N (SON) pool as a function of length of no-till and N fertilizer rates using various measures of N mineralization potential (i.e., chemical and biological assays). There is increasing evidence to suggest that the release of inorganic plant available N depends not only on the quantity of organic N present in the soil, but also the quality of organic N. Predicting N release from SON, thereby predicting fertilizer N requirements for subsequent crops, is essential to maximizing fertilizer use efficiency. The study was undertaken by sampling soils in 2012 and 2013 from an existing study site to determine if soil N availability differed in two adjacent fields converted to no-till 34 years [long-term no-till (LTNT)] and 11 years [short-term no-till (STNT)] previously at Indian Head, SK. Five rates of urea N (0, 30, 60, 90 and 120 kg N ha^{-1}) and seed-placed or side-banded monoammonium phosphate were assigned to plots within each field. These treatments were repeated on the same plots from 2002 to 2011. In 2012 and 2013, all P was side-banded and one set of N rate plots was assigned a constant rate of urea N (80 kg N ha^{-1}) while the other set retained the variable N rate treatments. Plots were rotated between wheat/canola across years. A biological aerobic incubation study revealed that soils from LTNT were able to supply approximately 20 more kg NO_3-N ha^{-1} during the early phases of the incubation and that the ability of STNT to supply NO_3-N slowed relative to the LTNT during the course of the incubation. It was concluded that the LTNT had a greater pool of readily-available N than the STNT, and was able to supply N over a sustained period. Higher levels of potentially available N in the LTNT soils is consistent with higher wheat yields in LTNT relative to STNT, irrespective of N fertilizer additions. These results underscore the importance of no-till practices in building soils that are capable of sustained nutrient supply and productivity.

LITERATURE REVIEW

The wide spread adoption no-till (direct seeding) systems on the Canadian Prairies began in the eighties. Conventional thinking, derived from the results of past research (Monreal and Janzen, 1993; Anderson, 1995; Franzluebbers and Arshad, 1996; McArthur et al., 2001; Pennock, 2003; Schnitzer et al., 2006; Leinweber et al., 2009), would suggest that soil improvement through improved carbon (C) sequestration and soil organic matter should occur. Furthermore, past research on the Prairies has found that no-till crop production systems are associated with improved crop yields (Lafond et al., 1996, 2006), profits (Gray et al., 1996; Zentner et al., 2002; Holm et al., 2006), and energy use efficiency (Zentner et al., 2004).

Nitrogen typically is regarded as the most important nutrient in crop production as it often limits both yield and protein production and frequently represents one of the most significant fertilizer input costs. Fertilizer N recommendations typically are based on point-in-time measurements of available inorganic N, coupled with presumed or predicted N mineralization during the growing season. Consequently, understanding N dynamics in soils managed as no-till cropping systems is imperative. Moreover, factors that may influence N dynamics, such as length of time under no-till management, must be considered.

Various studies have examined the impact of no-till on soil chemical constituents, including soil organic carbon (SOC) and soil organic nitrogen (SON). Less disturbance associated with no-till typically results in higher SOC and SON (e.g., Campbell et al. 1997b; West and Post, 2002; McConkey et al. 2003; Liang et al. 2004). These components of soil organic matter (SOM) play important roles in enhancing soil quality, including the size of the soil microbial community, which mediates soil nutrient cycling (Hamel et al. 2006). According to Lupwayi et al. (2004), no-till enhanced both the size and functional diversity of soil microorganisms. Helgason et al. (2009, 2010) reported that total, bacterial and fungal biomass was enhanced in no-till compared to conventional till soils, but there was no shift in the relative abundance of fungi versus bacteria in most instances. Enhanced microbial biomass, and hence potential to contribute to nutrient cycling, is consistent with the observation that N mineralization was enhanced in no-till soils (Soon and Clayton, 2003).

Investigating the impact of long-term no-till on nutrient cycling is challenging, as few scientifically defensible, controlled long-term sites are maintained, largely due to the commitment of resources and financial investment required to maintain sites over many years – yet long-term sites can provide a plethora of valuable information that otherwise can only be speculation. The current study was facilitated through access to experimental sites maintained through collaboration between Agriculture and Agri-Food Canada, Vale Farms Ltd. of Indian Head, and the Indian Head Agricultural Research Foundation. The experiments and the experimental design have been described elsewhere in detail (Lafond et al. 2011). Briefly, experiments were established in 2002 on a field managed under no-till since 1978 (long-term no-till, LTNT) and an adjacent field managed under no-till since 2001 (short term no-till, STNT). Up to 2011, the study included five rates of urea N (0, 30, 60 90 and 120 kg N ha^{-1}) and two P fertilizer placement methods (seed-placed vs side-banded). Lafond et al. (2011) determined that P placement methods had no long-term impact on crop yields. Thus, in 2012, all P was side-banded and one set of N rate treatments was assigned a constant rate of 80 kg N ha^{-1} of urea, while the other set retained the variable N rate treatments. A canola (*Brassica napus* L.) – spring wheat (*Triticum aestivum* L.) cropping sequence was superimposed on the plots. Lafond et al. (2011) reported that after 8 years, wheat grain yield was 14% greater for LTNT versus STNT and maximum grain N removal was 87 kg ha^{-1} for LTNT and 74 kg ha^{-1} for STNT. Grain protein concentration did not differ between LTNT and STNT. For canola, grain yield was 16% greater for LTNT than STNT, and more N fertilizer was required under STNT than LTNT (116 vs 106 kg N ha^{-1}) to achieve maximum yield. Canola seed protein concentration for LTNT was greater than for STNT at intermediate N fertilizer rates. Results from 2009 showed a "lack of convergence of grain yield responses to N between LTNT and STNT", despite the fact that N fertilizer rates were greater than the amount of grain N removed from the system. From this, these researchers speculated that LTNT must have had greater growing season N supplying power than STNT soils, which translated into improved productivity—an assertion that was supported by the greater levels of flag leaf N concentration in the LTNT. Furthermore, they conjectured that the

nutrient supplying power of soils under the LTNT soils may still be improving even after 30+ years of no-till management.

Lafond et al. (2011) postulated the STNT, and even the LTNT, were still in a ‘‘soil building’’ phase, and that the potential for these systems to have greater soil N supplying power existed. The desire to quantify the current soil N supplying power in the LTNT and STNT, and the practical importance N fertilizer management, served as the impetus for the current study. The objective of this study was to do a follow-up assessment of soil N availability in two adjacent fields converted to no-till 34 and 11 years previously.

MATERIALS AND METHODS

Site description

This study was part of a larger research project that began in 2009 that investigated long-term no-till (LTNT; converted to no-till in 1978) and short-term no-till (STNT; converted to no-till in 2001) management histories in two adjacent fields near Indian Head, Saskatchewan, Canada (50.42° North 103.58° West). As of 2012, the LTNT field had been in no-till production 34 years and the STNT field had been in no-till production 12 years. The study site is located in the thin Black soil zone, soil type is Oxbow loam (Orthic Black Chernozem or Typic Haplocryoll), soil texture is 58% sand, 26% silt and 16% clay, and SOC content (0 to 15 cm) was 2.25% for the LTNT field and 1.72% for the STNT field in the spring of 2003 (Lafond et al. 2011). See Lafond et al. (2011) for more information about the study site.

Experimental design

Two experimental sites were established. Within each study area, factorial combinations of five rates of granular urea N (46-0-0) (0, 30, 60, 90 and 120 kg N ha^{-1}) and seed-placed or side-banded monoammonium phosphate (11-52-0) at rates ranging from 10 to 15 kg P ha^{-1} (Table 3, Lafond et al. 2011) were assigned to three replicates of plots (3.96 m x 10.7 m = 43.37 m^2) arranged in a randomized complete block. The preceding treatments were

repeated on the same plots from 2002 to 2011. In 2012, all P was side-banded and one set of N rate treatments was assigned a constant rate of 80 kg N ha^{-1} of urea, while the other set retained the variable N rate treatments. Across years, a wheat-canola cropping sequence used; plots were seeded to spring wheat in 2002, 2004, 2006, 2008, 2010, and 2012 and to canola in alternating years for a wheat–canola rotation.

Plots were managed using typical management practices (weed control, etc.) for the region. Pertinent management information was summarized by Lafond et al. (2011) in Table 3. Specifically, plots were seeded with drill using commercial hoe openers spaced 30.48 cm apart with individual press wheels on each opener for precise seed placement. Nitrogen fertilizer was placed in sideband (as was P fertilizer) located 2.5 cm to the side and 7.5 cm below the seed. Potassium sulfate (K_2SO_4; 0-0-52-17) was broadcast on the soil surface in the fall prior to sowing canola at a rate of 88 kg ha^{-1} to provide 15 kg S ha^{-1}.

Data collection

Soil samples were collected in the spring of 2012 from the 0- to 15-cm and 15- to 30-cm intervals of the soil profile using a truck mounted hydraulic punch (single sample per plot), and in the spring of 2013 from the 0- to 5-cm and 5- to 15-cm intervals of the soil profile using a hand probe (5 samples per plot were bulked). Approximately 150 g of each soil sample was sieved using a 4.75 mm sieve for further chemical analyses. A number of measurements were made from these samples, including bulk density (Blake and Hartge 1986), inorganic nitrate and ammonium using 2 *M* KCl extract (Keeney and Nelson 1982) followed by colorimetrc analysis using a Technicon Autoanalyzer II (Labtronics Inc., Tarrytown, NY), hot KCl extractable N (Jalil et al. 2996), and total and organic soil C (Wang and Anderson, 1998). Potentially mineralizable N was estimated using a biological aerobic incubation method for samples collected in 2012, and a second anaerobic incubation method was used to assess potentially mineralizable N for samples collected in 2013. Both methods are described by Curtin and Campbell (2008). Briefly, for the aerobic incubation, 100 g of oven dry equivalent field moist soil mixed 1:1 with air dry acid-washed sand was packed into 30-cm long tubes (4.45 cm i.d.). The soils

were pre-leached with 200 mL of 0.01 M CaCl followed by 10 mL of a N-free nutrient solution (Fig. 1). Leachate was analyzed for inorganic N. Moisture contents were adjusted to approximate field capacity and samples were incubated for 16 weeks, with similar extractions occurring every two weeks.

Figure 1. Incubation vessels constructed from a clear polypropylene tube. Glass microfiber pads were Whatman 30 micron mesh, 1.6um glass microfiber filters (GF/A- Circles 55mm) cut both to properly fit the tube. The apparatus was held together with cyanoacrylate glue.

Statistical analyses

The two LTNT and STNT study areas were not replicated within year. Consequently, the effect of replicate was nested within history, and the tests for the effect of year, history, and year by history were included in the analysis but not reported (e.g., Linquist et al., 2008).

All data were analyzed with the following mixed model, and conducted using the PROC MIXED procedure of SAS (Littell et al., 2006; SAS Institute, 2011). Analyses considered the effects of replicate (nested within history) as random, the effect of tillage history, N rate type (constant or variable), and N fertilizer rate as fixed. Exploratory analyses revealed that residual variances were heterogeneous between tillage history. The AICc (corrected Akaike's information) model fit criterion confirmed whether the preceding model parameterization was better than a model not modeling residual variance heterogeneity. Variance heterogeneity was modeled using a repeated statement with the group option set to history. Contrasts were used to compare mean responses among the statistically significant treatment combinations.

Specific details for data collected in the individual experiments within this study were as follows. For the analysis of the 2012 data, the NH_4 data was not analyzed as much of the data were zero or nearly so. Furthermore, kg NO_3 ha^{-1} data for each time was summed with the previous time consequently resulting in accumulated NO_3 over the course of the experiment. The days after the start of the experiment (DAS) was considered as a class factor cross-classified with other fixed effects. The covariance for measurements made across time for the same plot was accounted for with a compound symmetry (all dates were equally correlated with each other) covariance structured that allows unique variance estimates for each DAS; heterogeneous compound symmetry (Littell et al., 2006; SAS Institute, 2011). The modeling of repeated measures was done separately for each tillage history using the group option set to history within the repeated statement. The corrected Akaike's Information Criterion (AIC_C) was used to ascertain the benefit of modeling repeated measures and variance heterogeneity.

Cumulative mineral N (N_{min}) data from the biological incubation was used to calculate potentially mineralizable N (N_0) using a nonlinear regression-iteration of a first order kinetic model, as described by Curtin and Campbell (2008):

$$N_{min} = N_o (1-e^{-kt}) \qquad \text{(eq. 1)}$$

Where N_{min} is cumulative N mineralized over time (t), N_o is potentially mineralized N, and k is the mineralization rate constant. The kinetics model failed to converge for the native site data, and thus this data are presented as means only.

The 2012 and 2013 soil N and C was analyzed separately for each year by depth combination, and the 2013 incubation data was analyzed separately for each depth.

RESULTS AND DISCUSSION

Soil characterization

Soil characterization focused on measures of N contributing to soil N supply and included inorganic N, and potentially mineralizable N assessed using an anaerobic incubation technique. The overall analysis of variance for data from soils sampled in spring 2012 (0 to 15 cm) and 2013 (0 to 5 and 5 to 15 cm) revealed few statistically significant ($P < 0.05$) effects (Table 1). One exception was the history by N rate type interactions that were statistically significant or approaching significance for NH_4-N variables (anaerobic NH_4 and NH_4-N) at the 5- to 15-cm depth. Further exploration of these interactions revealed that NH_4-N released during anaerobic incubation and inorganic mineral levels of extractable NH_4-N were greater for variable N rate compared with constant N-rate only for STNT (data not shown). The agronomic significance of this finding is not discussed here. The effect of management history cannot be quantitatively assessed as sites were not replicated, but it was apparent that anaerobic and mineral levels of NH_4-N, and total N were greater for LTNT than STNT (Table 2), particularly in the 0- to 5-cm depth.

Table 1. Analysis of variance (ANOVA) for anaerobic incubation data, and N levels from soils collected in 2012 (0-15) and 2013 (0-5 and 5-15 cm) at Indian Head.

Depth / Effect	Anaerobic NH4	NO3-N	NH4-N	Total inorganic N	Total Soil N
0-5 cm					
history	0.862	0.047	0.030	<0.001	0.323
nrate	0.701	0.915	0.152	0.462	0.754
history*nrate	0.463	0.636	0.591	0.340	0.620
type	0.470	0.192	0.545	0.126	0.795
history*type	0.209	0.761	0.489	0.205	0.087
nrate*type	0.270	0.720	0.740	0.682	0.318
history*nrate* type	0.813	0.685	0.867	0.637	0.741
5-15 cm					
history	0.032	0.004	0.245	0.034	0.885
Nrate	0.658	0.154	0.993	0.787	0.970
history*nrate	0.566	0.198	0.875	0.866	0.915
type	0.496	0.920	0.228	0.965	0.856
history*type	0.039	0.802	0.063	0.825	0.503
nrate*type	0.283	0.460	0.657	0.997	0.092
history*nrate* type	0.106	0.214	0.051	0.913	0.929
0-15 cm					
history		0.001	0.078	<0.001	0.427
Nrate		0.560	0.341	0.652	0.846
history*nrate		0.912	0.474	0.730	0.859
type		0.349	0.769	0.264	0.776
history*type		0.746	0.083	0.317	0.106
nrate*type		0.623	0.738	0.926	0.185
history*nrate* type		0.894	0.149	0.952	0.837

Table 2. Means for anaerobic incubation data, and N levels from soils collected in 2013 (0-5 and 5-15 cm) at Indian Head.

Management/N fertilizer rate (kg ha^{-1})	Anaerobic NH4-N release	NH_4-N	NO_3-N	Total N
0-5 cm		mg kg^{-1}		
LTNT				
0	82.2	0.23	0.68	35.2
30	66.1	0.17	0.58	34.7
60	61.9	0.28	0.57	28.1
90	84.9	0.24	0.79	30.5
120	77.6	0.19	0.82	36.9
LSD0.05	32.2	0.09	0.23	7.7
STNT				
0	69.2	0.33	0.68	23.6
30	77.5	0.29	0.88	27.2
60	75.8	0.31	0.87	27.0
90	74.9	0.26	0.88	29.6
120	80.2	0.21	0.88	30.1
LSD0.05	18.8	0.17	0.51	11.2
5-15 cm				
LTNT				
0	21.1	0.10	0.31	21.4
30	16.1	0.12	0.39	23.3
60	19.7	0.14	0.33	22.6
90	15.1	0.13	0.37	22.0
120	21.6	0.13	0.34	20.5
LSD0.05	15.0	0.10	0.17	7.2
STNT				
0	46.8	0.24	0.65	18.3
30	51.7	0.23	0.71	19.9
60	54.3	0.24	0.49	20.1
90	57.1	0.24	0.99	17.9
120	59.4	0.20	0.74	18.6
LSD0.05	14.2	0.13	0.36	4.6

Biological Aerobic Incubation (2012 soil samples)

Typically, NH_4-N levels in soil extracts from the biological incubation were far less than those for NO_3-N levels. Soil NH_4-N often was less than 1 kg NH_4 ha^{-1}, and exceeded 10 kg NH_4 ha^{-1} only for about 10% of data points. Moreover, as the incubation continued, NH_4-N levels were often below detection limits. Therefore, the statistical analysis of 2012 soil mineral N data only included NO_3-N data converted to a kg ha^{-1} basis using bulk density. Furthermore, NO_3-N data were accumulated (summed) across time (i.e., over the entire incubation period) to reflect N supplying power of the different cropping systems.

ANOVA for fixed effects (N rate, N rate type, and interactions with time) indicated that accumulated NO_3-N did not differ ($P > 0.05$) among the treatments (Table 3). The linear and quadratic effects of time were statistically significant. The trend lines for the accumulation of mineral NO_3-N indicated that the accumulation NO_3-N release was initially linear (about 0.6 kg NO_3-N ha^{-1} per day) and then began to slow at about 40 days after the start of the incubation (Fig. 2). Predicted responses based on average model parameter estimates N_{min} and N_o indicate that LTNT continued to supply mineral N at a higher level than the STNT throughout the course of the incubation. Specifically, the rate constant, k, was two times greater in LTNT (0.0428) than STNT (0.0244), and the estimate of potentially mineralizable N, N_o, was also higher in LTNT (93.3 kg ha^{-1}) versus STNT (76.8 kg N ha^{-1}). It was apparent that the LTNT was able to supply about 20 kg NO_3-N ha^{-1} more than was supplied by the STNT during the initial rapid release of mineral N (i.e., during the first 14 d). As the incubation progressed, it appeared that the ability of STNT to supply NO_3-N was slowed relative to the LTNT. Furthermore, covariance parameter estimates indicated that LTNT responses were more variable than for STNT (Table 2). It is suspected that this greater level of random variability for LTNT also resulted in diminished statistical power (i.e., greater SE) for tests associated with the fixed effect of history. In conclusion, it seems that the LTNT has a greater pool of readily available NO_3-N as compared to the STNT, and the variability in LTNT N release was more variable, suggesting that N supply may be more highly sensitive to environmental conditions. Low levels of cumulative mineralized N (N_{min}) associated with the soils from the native site is surprising, as one might expect these soils to

release significant amounts of N. However, it is likely that these soils were both producing and consuming N very quickly because the presence of only partially decomposed organic matter (roots, etc.) would contribute to significant immobilization of newly mineralized N. Thus, because the aerobic incubation measured net mineralization and not gross mineralization, N_{min} for the native soils appeared to be suppressed in native soils.

Table 3. Analysis of variance (ANOVA) for aerobic incubation NO_3-N data from soils collected in 2012 at Indian Head.

Effect	Aerobic Incubation NO_3-N	
	(P value)	
das	< 0.001	
history	0.013	
das*history	0.509	
type	0.706	
das*type	0.734	
history*type	0.998	
das*history*type	0.631	
nrate	0.803	
das*nrate	0.999	
history*nrate	0.849	
das*history*nrate	1.000	
nrate*type	0.950	
das*nrate*type	0.997	
history*nrate*type	0.575	
das*hist*nrate*type	0.923	
	(Covariance estimate)[z]	
Rep(history)	33	
LTNT (DAS)		
1	681	**
15	1000	**
29	1224	**
43	1488	**
58	1841	**
71	2209	**
85	2487	**
CSH	0.98	**
STNT (DAS)		
1	72	**
15	105	**
29	166	**
43	200	**
58	277	**
71	403	**
85	403	**
CSH	0.93	**

[z] Variance estimates for each DAS (days after start) and a compound symmetry (CSH) estimate. The statistical significance of the variance estimates are indicated as follows: '*' = 0.05 ≥ P value ≥ 0.01; and '**' = P value < 0.01.

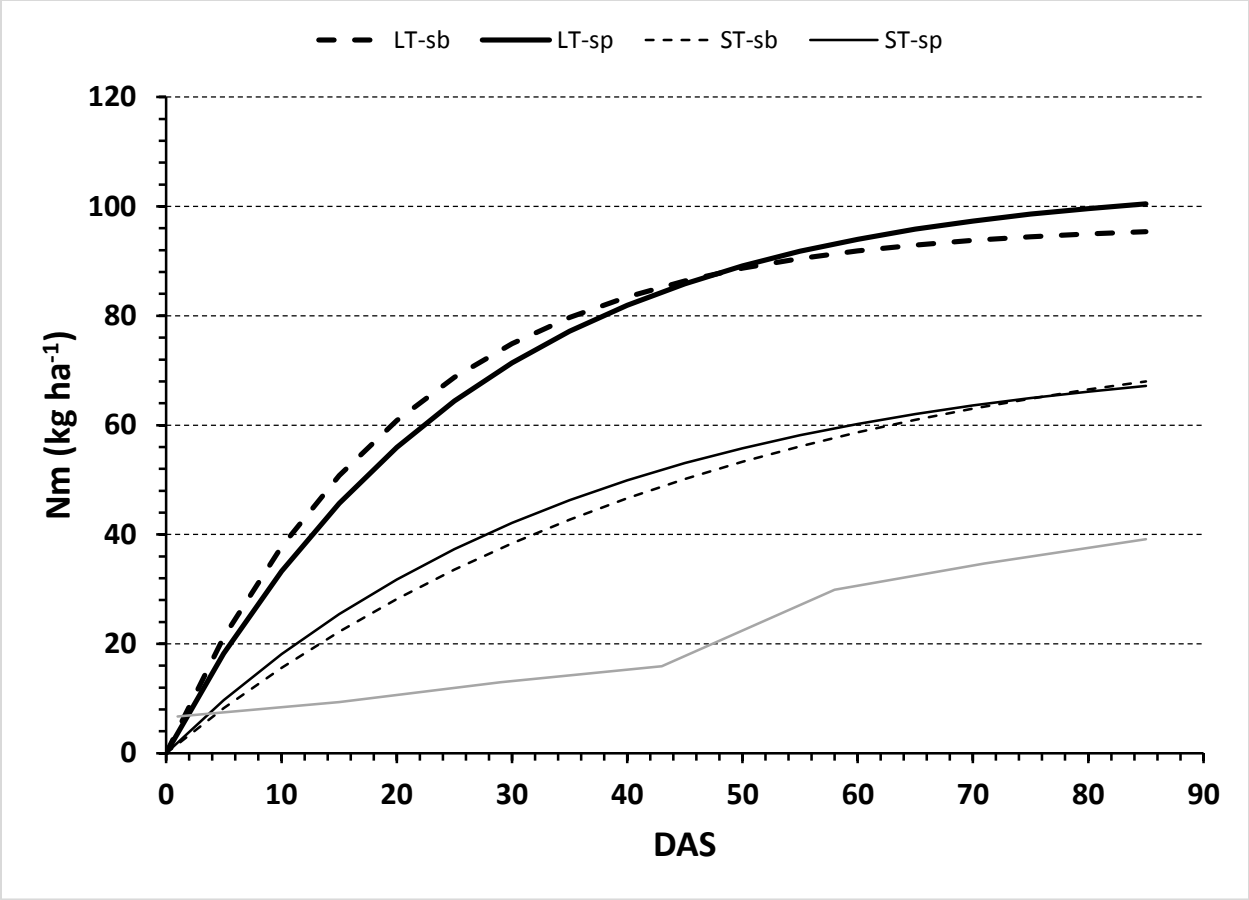

Figure 2. Predicted cumulative N mineralization from the long-term (16-wk) biological incubation (LT = long term; ST = short term; sb = variable rate (previously sideband P); sp = constant rate (previously seed placed P). The grey line represents N accumulation means from the native site (the kinetics model failed to converge).

The results from the biological aerobic incubation support the observations and speculations of Lafond et al. (2011). In this earlier study, it was reported that maximum spring wheat grain yield for LTNT was 14% higher than on STNT, even when similar rates of fertilizer N were applied. Moreover, maximum grain protein was similar between the different management histories, despite higher grain yields in LTNT with similar fertilizer N rates. These led the authors to postulate that STNT is in a "soil building stage" thus limiting the N

supplying power of the soil. Results from the biological aerobic incubation confirm that LTNT soil had a greater capacity to mineralize N over a 16 week incubation period, and provides credence to the assertion that maintaining no-till over longer time frames continues to build the potential productivity of the soil, and that intermittent tillage may compromise these benefits.

Conclusions

Earlier assessments of wheat grain yield and grain protein content led to the postulation that soils converted to no-till management may be in a "soil building" phase for several years, during which inorganic N supply may be somewhat limited for crop production as the soil sequesters both C and N in the soil organic matter fraction (Lafond et al. 2011). Indeed, it was earlier reported by Lafond et al. (2011) that even when N fertilizer is supplied, STNT soils may require more fertilizer N than LTNT to achieve the same grain yields because the STNT is "consuming" N in the soil building process. The benefits of this soil building process, however, are observed in LTNT, which appears to support higher rates of N-cycling than the STNT. We confirmed this using a long-term aerobic incubation, in which N mineralized during the incubation period was monitored. During the incubation, the LTNT soils mineralized more N than the STNT throughout a 16-week period. This LTNT soils provide greater benefits in terms of N supply than STNT. It is not known when soils would normally transition from the soil building stage, but these results suggest that even after more than 30 years of no-till, the soils may still be improving, particularly when N fertilizer is applied at rates meeting crop needs.

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