Sustainable Agriculture Research; Vol. 4, No. 4; 2015
ISSN 1927-050X E-ISSN 1927-0518
Published by Canadian Center of Science and Education

Effects of Short-term Tillage of a Long-term No-Till Land on Available N and P in Two Contrasting Soil Types

Miles Dyck[1], Sukhdev. S. Malhi[1,2], Marvin Nyborg & Dick Puurveen[1]

[1] Department of Renewable Resources, University of Alberta, Edmonton, AB, Canada

[2] Previous Address: Agriculture and Agri-Food Canada, Melfort, Saskatchewan, Canada

Correspondence: Miles Dyck, Department of Renewable Resources, University of Alberta, Edmonton, AB, Canada, E-mail: mdyck@ualberta.ca

Received: May 5, 2015 Accepted: June 25, 2015 Online Published: August 21, 2015

doi:10.5539/sar.v4n4p27 URL: http://dx.doi.org/10.5539/sar.v4n4p27

Abstract

The effects of short-term (4 years) tillage (hereafter called reverse tillage [RT]) of land previously under long-term (29 or 30 years) no-till (NT), with straw management (straw removed [S_{Rem}] and straw retained [S_{Ret}]) and N fertilizer rate (0, 50 and 100 kg N ha^{-1} in S_{Ret}, and 0 kg N ha^{-1} in S_{Rem} plots) were determined in autumn 2011 on ammonium-N, nitrate-N and extractable P in the 0-7.5, 7.5-15 and 15-20 cm soil layers at Breton (Gray Luvisol [Typic Cryoboralf] loam) and Ellerslie (Black Chernozem [Albic Argicryoll] loam), Alberta, Canada. There was no significant effect of RT and straw on ammonium-N, nitrate-N and extractable P in soil. Ammonium-N in soil increased significantly (but small) with N rate in many cases at both sites. Nitrate-N in soil increased with increasing N rate from 0 to 100 kg N ha^{-1} rate at Ellerslie, and up to 50 kg N ha^{-1} rate at Breton. Etractable P in soil decreased markedly with increasing N rate up to 100 kg N ha^{-1} at Breton and up to 50 kg N ha^{-1} at Ellerslie. In summary, increased N fertilizer rates were usually associated with decreased extractable P and increased nitrate-N in soil, but RT and straw had no effect on these nutrients in soil.

Keywords: dynamic organic fractions, N fertilizer, organic C and N, pre-seeding tillage, reverse tillage, soil quality, straw management

1. Introduction

In the Prairie Provinces of Canada, farmers traditionally used tillage for seedbed preparation to facilitate seeding operations, seed germination and weed control. Previous research has shown that tillage, especially when combined with summer fallow, can lead to deterioration of soil quality by diminishing organic C, aggregation, water storing capacity and nutrient supplying power, and can increase the potential for soil erosion (McGill et al., 1988; Lal et al., 1990). In the past several decades, no-tillage (NT, also called zero-tillage, or direct seeding) has gained popularity, because of its potential to enhance storage of water in soil by proper snow management/conservation, improvement in soil fertility/productivity, aggregation/tilth, lower requirement for labour, fuel and machinery, and increase in economic returns compared to conventional tillage (CT) (Selles et al., 1984; Malhi et al., 1988; H. Singh & K. P. Singh, 1994; Larney et al., 1997). However, long-term NT can increase: 1) infestation of perennial grassy weeds, such as quackgrass (Malhi et al., 1988; Campbell et al., 1990; Tessier et al., 1990); 2) stratification of nutrients, especially P, in the surface soil (Grant and Lafond, 1994; Crozier et al., 1999; Lupway et al., 2006; Baan et al., 2009; Jones et al., 2009); 3) emergence of herbicide-resistant perennial weeds (Donald, 1990; Derksen et al., 1993); 4) relatively cool and wet surface soil in spring (Johnson & Lowery, 1985; Jones et al., 1985; Malhi & O'Sullivan, 1990; Wolfe & Eckert, 1999) which can delay seeding and slow crop emergence/early growth, and increase in the potential of nutrient loss in surface water run-off which may cause pollution of water bodies (Ferguson et al., 1996). In addition, in areas where large amounts of crop residue/straw are produced and accumulate on the soil surface, it may be difficult to place the crop seeds properly into the soil, resulting in poor/sporadic germination, especially when proper direct-seeding drills are not available to facilitate seeding.

Therefore, despite the advantages of long-term no-till, producers may wish to introduce tillage occasionally for the purposes of weed, disease and residue control (Irvine et al., 2003). In fact, there is evidence to suggest that "strategic" tillage does not have any long-term negative impacts to crop yields, weed and disease populations or soil quality (Irvine et al., 2003). However, there is still very limited research on the effects of tillage of previously long-term NT soil on crop yield and nutrient uptake and soil fertility on farm fields in Canada (Campbell et., 1988, 1996; Baan et al., 2009), especially in the Parkland region of western Canada where large quantities of crop residue are produced and left on land after harvest. The objectives of this study were to examine the effects of short-term (2 or 3 years) pre-seeding shallow tillage (hereafter called reverse tillage – RT) of land previously under long-term (29 or 30 years) NT on crop yield and nutrient uptake [seed and straw yield, N and P uptake in seed and straw of annual cereals/oilseeds]; soil quality [total organic C (TOC) and N (TON), light fraction organic C (LFOC) and N (LFON) and mineralizable N (N_{min}) in the 0-7.5 and 7.5-15 cm soil layers]; and soil fertility [nitrate-N, ammonium-N and extractable P, in the 0-7.5, 7.5-15 and 15-20 cm soil layers] in two contrasting soil types (a Gray Luvisol soil at Breton and a Black Chernozem [Albic Argicryoll] soil at Ellerslie, Alberta, Canada.). This paper discusses the effects of RT on the amounts of available N and P in soil.

2. Methods

2.1 Location and Experimentation

The field experiments were conducted at Breton (53°07'N, 114°28'W; elevation 830 m) and Ellerslie (53°25'N, 113°33'W; elevation 692 m), Alberta, Canada. The Breton area belongs to ecoregion Peace Lowland/Boreal Transition with a rolling landscape. The soil was an Orthic Gray Luvisol (Typic Cryoboralf), with loam texture, pH of 6.6 and initial total C concentration of 13.75 g C kg^{-1}. The mean annual precipitation of the area is 475 mm and the growing season is from May to August. Approximately 60% of the total precipitation occurs in the growing season. This area has 2356 growing degree days (GDD) at >0 ^{o}C and 1335 GDD at >5 ^{o}C, 118 days frost free period, mean growing season precipitation 335 mm (range of 182 to 514 mm) and a growing season mean temperature of 14 ^{o}C (7 ^{o}C to 20 ^{o}C). The Ellerslie area belongs to the Aspen Parkland ecological region, which is characterized by a flat glacio-lacustrine landscape. The soil is a Black Chernozem (Albic Argicryoll), with loam texture, pH 6.0 and initial total organic C concentration of 56.45 g C kg^{-1}. The mean annual precipitation of the area is about 450 mm and the growing season is from May to August. Approximately 60% of the total precipitation occurs in the growing season (335 mm with a range of 190 to 440 mm). This area has growing degree days (GDD) of 2419 at >0 ^{o}C and GDD of 1402 at >5 ^{o}C, a 120 day frost free period, and a mean daily temperature of 14 ^{o}C (8 ^{o}C to 21 ^{o}C) in the growing season.

Table 1. Description of treatments sampled in autumn 2011 at Breton (Gray Luvisol) and Ellerslie (Black Chernozem), Alberta, Canada (experiments established in autumn 1979)

Treatment				
No.	ID	Tillage system	Straw management	Rate of N (kg N ha^{-1})
1a	$NTS_{Rem}0$	No-tillage	Straw removed	0
1b	$RTS_{Rem}0$	Reverse tillage	Straw removed	0
4a	$NTS_{Ret}0$	No-tillage	Straw retained	0
4b	$RTS_{Ret}0$	Reverse tillage	Straw retained	0
3a	$NTS_{Ret}50$	No-tillage	Straw retained	50
3b	$RTS_{Ret}50$	Reverse tillage	Straw retained	50
6a	$NTS_{Ret}100$	No-tillage	Straw retained	100
6b	$RTS_{Ret}100$	Reverse tillage	Straw retained	100

The original experiments with NT and CT with various straw management (removed [S_{Rem}] and retained [S_{Ret}]) and N rate (0, 50 and 100 kg N ha^{-1}) treatments were established in autumn 1979 (with the first growing season in 1980) at the University of Alberta Experimental Farms Breton and Ellerslie, Alberta to examine the influence of fertilizer N-straw management-tillage interactions on crop productivity and soil properties (Malhi et al. 2010, 2011a, 2011b). The treatments were arranged in a randomized complete block design in four replications. Initially, the plots were planted to a continuous barley (*Hordeum vulgare* L.) rotation with two tillage systems (conventional tillage [CT] and zero tillage [ZT]), two straw treatments (straw removed [S_{Rem}] and straw retained [S_{Ret}]) and two N treatments (0 and 56 kg N ha^{-1}) (Nyborg et al., 1995). However in 1991, another N treatment was added (100 kg N ha^{-1}) and the 56 kg N ha^{-1} was reduced to 50 kg N ha^{-1} (Table 1). At the same time, the barley rotation was changed to spring wheat (*Triticum aestivum* L.). In 1997, the rotation was then changed to a barley-wheat-canola (*Brassica napus* L.) rotation. Individual plots were 2.8 m × 6.9 m. Plots under CT were tilled twice, once in the autumn and once in the spring, with a chisel cultivator followed by a coil packer. The ZT plots did not undergo any disturbance, except for seeding drill. The original NT and CT treatments were seeded to various crops in rotations from 1980 to 2010 growing seasons at Breton and from 1980 to 2009 growing seasons at Ellerslie. The NT treatments were split into two (in spring 2010 at Breton and in spring 2009 at Ellerslie) to include: 1) Control NT treatment with no pre-seeding tillage; and 2) Tilled treatment with one tillage using rotary tiller in spring prior to seeding (hereafter called reverse tillage [RT]). The crop was harvested every year from 1980 to 2012 for seed, straw or whole plant yield. In autumn 2011, soil samples were taken from each plot in 8 treatments (Table 1) after crop harvest. The soil samples were then analyzed for available N and P.

2.2 Soil Sampling and Sample Preparation

Soil cores from 8 locations in each plot were collected from the 0-7.5, 7.5-15 and 15-20 cm layers using a 2.4 cm diameter coring tube. Bulk density of the soil was determined by the core method (Culley 1993). The soil samples were air dried at room temperature after removing any coarse roots and easily detectable crop residues, and ground to pass a 2-mm sieve.

2.3 Chemical Analysis

The ground soil samples were analysed for ammonium-N (NH_4-N), nitrate-N (NO_3-N), extractable P (phosphate-P - PO_4-P). Nitrate-N and ammonium-N were extracted using 1:5 soil: 2M KCl solution and their concentrations in extracts determined with a Technicon Autoanalyzer II (Tecnicon Industrial Systems 1973a, 1973b). Phosphorus was extracted using Kelowna extract (Qian et al., 1994) and measured colorimetrically on a Technicon Autoanalyzer (Tecnicon Industrial Systems, 1977).

2.4 Statistical Analysis

The data on ammonium-N, nitrate-N and extractable P were subjected to analysis of variance (ANOVA) using procedures as outlined in SAS (SAS Institute Inc, 2004). Significant ($p \leq 0.05$, or $p \leq 0.10$ when $p \leq 0.05$ not significant) differences between each treatment were determined using LSmeans (Proc GLM, SAS 6.1 for windows). Least significant difference test ($LSD_{0.05}$, or $LSD_{0.10}$ when $LSD_{0.05}$ not significant) for various parameters was used to compare all treatment means, tillage systems (NT vs. RT), straw management (S_{Rem} vs. S_{Ret} for the zero-N treatment) and N fertilizer rates (0, 50 and 100 kg N ha^{-1}).

3. Results

At both sites, there were some significant interaction of tillage, straw and N rate factors on the amount of ammonium-N in soil, but these differences were very small (1 - 4 kg NH_4-N ha^{-1}), and individual factors showed some significant effects on soil ammonium in some depths (Table 2). Averaged over straw and N treatments, ammonium in RT plots was marginally lower (P<0.10) than NT for the 0-7.5 cm depth. Averaged over tillage and N rates, ammonium in the S_{ret} plots were significantly lower compared to S_{rem} plots in the 7.5-15 cm depth. The amount of ammonium-N in soil increased significantly (but small) with N rate in many cases at both sites. Ammonium-N in the surface 20 cm ranged from 8.0 to 12.2 kg N ha^{-1} at both sites, suggesting that soil ammonium-N was not very sensitive to fertilizer applications or soil type.

Nitrate-N in different soil layers were relatively low (even after 32 years of N fertilization) at both sites, particularly at Breton where nitrate-N in the 15-20 cm soil layer was extremely low (Table 3). At Ellerslie, however, there were significant straw, tillage, N rate interactions with respect to soil nitrate in all soil layers, and only marginally significant interactions (P<0.10) in the 7.5-15cm layer at Breton. The majority of the interaction among treatments at Ellerslie appears to occur in the straw treatments at the 0 N rate. In the zero-N treatment at Ellerslie, compared to NT, nitrate-N in the 0-20 cm soil increased significantly with RT in the S_{Rem} treatment (7.8 kg N ha^{-1} vs. 14.8 kg N ha^{-1}), but there was no effect of RT in the S_{Ret} treatment. When soil nitrate was averaged across all N rates and straw treatments, there was no significant difference in between RT and NT at both sites. Averaged across two tillage systems, S_{Rem} treatments tended to have greater nitrate-N in soil than the S_{Ret} treatment at Ellerslie. At Breton, RT and S_{Ret} treatments had no positive significant effect on the amount of nitrate-N in any soil layer compared to their corresponding treatments. In the 0-20 cm soil, nitrate-N increased with increasing N rate from 8.4 kg N ha^{-1} 0 kg N ha^{-1} to 25.5 kg N ha^{-1} at 100 kg N ha^{-1} rate at Ellerslie. Nitrate-N in soil also increased with N fertilization up to 50 kg N ha^{-1} rate at Breton but the amounts of nitrate-N in soil were very low (i.e., from 2.0 kg N ha^{-1} at 0 kg N ha^{-1} to 3.8 kg N ha^{-1} 50 kg N ha^{-1}).

Significant interactions between tillage, straw and N rate factors were observed with respect to extractable P from the 0-7.5 cm and 0-20 cm layers at Breton and Ellerslie (Table 4). Extractable P in these two layers tended to decrease with increasing N rate and TR. The TR effects are most apparent in the 0-7.5 soil layer and less apparent in 0-20 cm layer Extractable P in the 0-20 cm soil decreased markedly with increasing N rate up to 100 kg N ha^{-1} at Breton (from 83.2 kg P ha^{-1} at 0 kg N ha^{-1} to 52.6 kg P ha^{-1} at 100 kg N ha^{-1}) and up to 50 kg N ha^{-1} at Ellerslie (from 81.5 kg P ha^{-1} at 0 kg N ha^{-1} to 48.6 kg P ha^{-1} at 50 kg N ha^{-1}) (Table 4). With respect to straw, extractable P in the 0-7.5 and 0-20 cm layers was lower in the S_{rem} treatments at Breton, regardless of tillage. Averaged across two tillage systems at zero-N rate, extractable P in the 0-20 cm soil was 83.2 kg P ha^{-1} (S_{ret}) vs. 76.8 kg P ha^{-1} (S_{rem}) at Breton. At Ellerslie, the straw treatments showed a stronger interaction with tillage. For example, in the 0-20 cm soil depth, compared to NT, RT had much greater extractable P in the S_{Rem} treatment at Ellerslie (76.8 kg P ha^{-1} vs. 81.6 kg P ha^{-1}) and much lower extractable P in the S_{Ret} (87.8 kg P ha^{-1} vs. 75.3 kg P ha^{-1}).

Table 2. Effect of long-term tillage, straw and N rate on ammonium-N in soil in autumn 2011 at Breton ((Gray Luvisol soil) and Ellerslie (Black Chernozem soil), Alberta, Canada (experiments established in autumn, 1979)

Treatment[z] (tillage/straw/kg N ha^{-1})	Ammonium-N (kg N ha^{-1}) in soil layers (cm) at Breton				Ammonium-N (kg N ha^{-1}) in soil layers (cm) at Ellerslie			
	0-7.5	7.5-15	15-20	0-20	0-7.5	7.5-15	15-20	0-20
Treatment mean								
NTS_{Rem}0	3.4	3.6	2.6	9.6	3.4	3.7	2.4	9.5
RTS_{Rem}0	2.9	3.7	2.9	9.5	3.6	3.6	2.7	9.9
NTS_{Ret}0	3.3	3.3	2.5	9.1	3.3	3.6	2.4	9.3
RTS_{Ret}0	2.7	3.1	2.2	8.0	3.2	3.4	2.3	8.9
NTS_{Ret}50	4.1	3.7	2.6	10.4	4.2	4.0	2.8	11.0
RTS_{Ret}50	3.3	4.0	2.4	9.7	3.5	4.1	2.5	10.1
NTS_{Ret}100	4.5	3.5	2.4	10.4	4.8	5.0	2.4	12.2
RTS_{Ret}100	4.1	3.8	2.7	10.6	4.3	4.4	2.5	11.2
$LSD_{0.05}$	0.8	0.9	0.6	1.9	0.7	0.7	0.8	1.5
SEM (Prob)	0.26**	0.31^{ns}	0.20^{ns}	0.63^{ns}	0.24***	0.25**	0.28^{ns}	0.51**
Tillage effect								
NT mean	3.8	3.5	2.5	9.8	3.9	4.0	2.5	10.4
RT mean	3.3	3.7	2.5	9.5	3.7	3.9	2.5	10.1
$LSD_{0.05}$	0.6	0.4	0.3	1.0	0.5	0.5	0.4	1.0
SEM (Prob)	$0.20^{\bullet}$	0.15^{ns}	0.11^{ns}	0.36^{ns}	0.18^{ns}	0.17^{ns}	0.13^{ns}	0.36^{ns}
Straw effect at 0 N								
S_{Rem}mean	3.2	3.6	2.7	9.5	3.5	3.6	2.6	9.7
S_{Ret} mean	3.0	3.2	2.4	8.6	3.3	3.5	2.3	9.1
$LSD_{0.05}$	0.6	0.2	0.5	1.0	0.6	0.3	0.5	0.9
SEM (Prob)	0.18^{ns}	0.06**	0.16^{ns}	0.30*	0.19^{ns}	0.10^{ns}	0.16^{ns}	0.29^{ns}
N rate effect with S_{Ret}								
0 mean	3.0	3.2	2.4	8.6	3.3	3.5	2.3	9.1
50 mean	3.7	3.8	2.5	10.0	3.8	4.0	2.7	10.5
100 mean	4.3	3.7	2.5	10.5	4.6	4.7	2.5	11.8
$LSD_{0.05}$	0.7	0.6	0.4	1.4	0.5	0.6	0.4	1.1
SEM (Prob)	0.22**	0.20^{ns}	0.14^{ns}	0.45*	0.16***	0.19**	0.14^{ns}	0.36***

[z]NT = No-tillage, RT = Reverse tillage, S_{Rem} = Straw removed, S_{Ret} = Straw retained, 0, 50 and 100 kg N ha^{-1}.

•, *, **, *** and ns refer to significant treatment effects in ANOVA at $P \le 0.10$, $P \le 0.05$, $P \le 0.01$, $P \le 0.001$ and not significant, respectively.

4. Discussion

Despite some significant statistical interactions, the effects of RT, straw management and N fertilization on soil ammonium-N were small, as also found in our previous studies on these soils (Malhi et al., 2010, 2011b). This suggests that ammonium-N is quickly converted to nitrate soon after ammonium-N is mineralized from the soil organic matter, resulting in little or no build-up of ammonium-N in soil over time under normal soil-climatic conditions.

Table 3. Effect of long-term tillage, straw and N rate on nitrate-N in soil in autumn 2011 at Breton ((Gray Luvisol soil) and Ellerslie (Black Chernozem soil), Alberta, Canada (experiments established in autumn, 1979)

Treatment[z] (tillage/straw/kg N ha^{-1})	Nitrate-N (kg N ha^{-1}) in soil layers (cm) at Breton				Nitrate-N (kg N ha^{-1}) in soil layers (cm) at Ellerslie			
	0-7.5	7.5-15	15-20	0-20	0-7.5	7.5-15	15-20	0-20
Treatment mean								
$NTS_{Rem}0$	1.9	0.6	0.3	2.8	4.3	2.2	1.3	7.8
$RTS_{Rem}0$	1.5	0.9	0.6	3.0	7.6	5.2	2.0	14.8
$NTS_{Ret}0$	0.9	0.5	0.3	1.7	4.9	3.1	1.2	9.2
$RTS_{Ret}0$	1.1	0.7	0.5	2.3	4.0	2.5	1.1	7.6
$NTS_{Ret}50$	1.9	1.0	0.5	3.4	7.6	4.2	1.8	13.6
$RTS_{Ret}50$	2.3	1.4	0.6	4.3	6.2	5.1	2.9	14.2
$NTS_{Ret}100$	1.7	0.8	1.4	3.9	16.8	7.7	3.5	28.0
$RTS_{Ret}100$	1.9	1.2	0.6	3.7	14.1	6.6	2.5	23.2
$LSD_{0.05}$	1.3	0.5	0.8	2.1	5.5	2.8	1.8	9.0
SEM (Prob)	0.42^{ns}	0.17*	0.26^{ns}	0.69^{ns}	1.89***	0.97**	$0.61^{\bullet}$	3.04***
<u>Tillage effect</u>								
NT mean	1.6	0.7	0.6	2.9	8.4	4.3	2.0	14.7
RT mean	1.7	1.0	0.5	3.2	8.0	4.9	2.1	15.0
$LSD_{0.05}$	0.7	0.3	0.4	1.1	4.2	1.9	1.0	6.7
SEM (Prob)	0.22^{ns}	0.10*	0.15^{ns}	0.38^{ns}	1.46^{ns}	0.65^{ns}	0.35^{ns}	2.30^{ns}
<u>Straw effect at 0 N</u>								
S_{Rem}mean	1.7	0.8	0.4	2.9	5.9	3.7	1.7	11.3
S_{Ret} mean	1.0	0.6	0.4	2.0	4.4	2.8	1.2	8.4
$LSD_{0.05}$	0.7	0.3	0.2	0.8	2.8	1.9	0.7	5.3
SEM (Prob)	0.22*	0.10^{ns}	0.07^{ns}	0.24*	0.90^{ns}	0.62^{ns}	0.22^{ns}	1.70^{ns}
<u>N rate effect with S_{Ret}</u>								
0 mean	1.0	0.6	0.4	2.0	4.4	2.8	1.2	8.4
50 mean	2.1	1.2	0.5	3.8	6.9	4.6	2.4	13.9
100 mean	1.8	1.0	1.0	3.8	15.4	7.1	3.0	25.5
$LSD_{0.05}$	0.6	0.4	0.7	1.3	4.4	2.2	1.4	7.0
SEM (Prob)	0.21**	0.13*	0.22^{ns}	0.43*	1.47***	0.72**	0.47*	2.35***

[z]NT = No-tillage, RT = Reverse tillage, S_{Rem} = Straw removed, S_{Ret} = Straw retained, 0, 50 and 100 kg N ha^{-1}.

•, *, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Tillage (CT or RT) is expected to increase the amount of nitrate-N soil by increasing mineralization of N from soil organic matter compared to NT (Malhi & Nyborg, 1987; Nyborg & Malhi, 1989). However, in our study, RT and S_{Ret} did not show any significant effect on residual nitrate-N in soil at both sites compared to the corresponding NT and S_{Rem} treatments after 32 years. Similarly, earlier studies in Saskatchewan (Nuttall et al., 1986) and Alberta (Malhi et al., 2006, 2010; Malhi & Lemke, 2007) have also shown no effect of tillage or straw management on residual soil nitrate-N. This lack of difference in residual nitrate-N in soil due to RT or S_{Ret} in this study could be due to uptake of all mineralized nitrate-N by crops in the growing seasons, resulting in little or no additional residual nitrate-N in soil after harvest compared to NT, as evidenced by greater crop yield and N uptake with RT and S_{Ret} than corresponding NT and S_{Rem} treatments (Malhi et al., 2011b, 2015).

Previous studies have shown significant increases in residual nitrate-N in soil after long-term applications of N fertilizer, especially at high N rates (Malhi et al., 1991, 2002, 2009; Guillard et al., 1995). Similarly, in our study, there was an increase in residual nitrate-N in the 0-20 cm soil depth due to N fertilization, but the amounts were relatively small particularly at Breton, even after 32 annual applications of N fertilizer, as also suggested in our previous report (Malhi et al., 2010). There are several possible reasons for these trends. For example, the rate of N in the present study was near or below the rate needed for optimum yield in this soil-climatic region (Mooleki et al., 2010). Also, a portion of the applied N, especially under NT and when straw was retained, may have been immobilized into the soil organic N pool (Malhi et al., 1996). In addition, it is also possible that a portion of the residual soil nitrate-N may have been lost as gaseous N after occasional heavy rainfalls that often occur during summer and/or autumn in this region (Meek et al., 1982; Lessard et al., 1996). The N loss may also have been due to leaching but there was no concrete evidence of leaching because soils in this study were sampled to only 20 cm depth. However, in our previous publication (Malhi et al. 2010) there was an evidence of downward movement of nitrate-N in the soil profile to 90 cm depth of soil sampled in spring 2007. In any case, any nitrate-N leaching below the root zone can be an economic loss to producers, as well as further deep leaching over time can contaminate groundwater and become a potential risk to water quality (Zhang et al., 1996; Vasconcelos et al., 1997; Yuan et al., 2000). The findings suggest the need for deep soil sampling up to 3 or 4 m depth in order to make valid conclusions related to nitrate leaching losses in this on-going study.

Table 4. Effect of long-term tillage, straw and N rate on extractable P in soil in autumn 2011 at Breton ((Gray Luvisol soil) and Ellerslie (Black Chernozem soil), Alberta, Canada (experiments established in autumn, 1979)

Treatment[z] (tillage/straw/kg N ha^{-1})	Extractable P (kg P ha^{-1}) in soil layers (cm) at Breton				Extractable P (kg P ha^{-1}) in soil layers (cm) at Ellerslie			
	0-7.5	7.5-15	15-20	0-20	0-7.5	7.5-15	15-20	0-20
Treatment mean								
$NTS_{Rem}0$	57.4	15.7	2.8	75.9	54.5	18.6	1.7	76.8
$RTS_{Rem}0$	53.0	16.4	8.2	77.6	50.3	28.6	2.7	81.6
$NTS_{Ret}0$	66.9	13.6	3.1	83.6	63.2	21.8	2.8	87.8
$RTS_{Ret}0$	53.9	25.4	3.5	82.8	52.6	20.1	2.6	75.3
$NTS_{Ret}50$	43.7	11.7	3.1	58.5	37.6	12.6	2.3	52.5
$RTS_{Ret}50$	35.7	20.3	4.0	60.0	20.1	14.1	10.7	44.9
$NTS_{Ret}100$	39.4	10.7	2.6	52.7	36.0	14.1	2.4	52.5
$RTS_{Ret}100$	33.4	14.9	4.1	52.4	30.7	16.9	2.5	50.1
$LSD_{0.05}$	14.6	10.7	6.1	19.0	11.9	13.9	9.2	21.5
SEM (Prob)	4.82**	3.53^{ns}	2.00^{ns}	6.28**	4.05***	3.87^{ns}	3.13^{ns}	7.31**
Tillage effect								
NT mean	51.8	12.9	2.9	67.6	47.8	16.8	2.8	67.4
RT mean	44.0	19.3	4.9	68.2	38.4	19.9	4.6	62.9
$LSD_{0.05}$	11.2	5.3	2.8	14.0	11.2	7.1	4.5	15.4
SEM (Prob)	3.81^{ns}	1.78*	0.94^{ns}	4.74^{ns}	$3.86^{\bullet}$	2.44^{ns}	1.54^{ns}	5.32^{ns}
Straw effect at 0								

N								
S_{Rem}mean	55.2	16.1	5.5	76.8	52.4	23.6	3.2	79.2
S_{Ret} mean	60.4	19.5	3.3	83.2	57.9	20.9	2.7	81.5
$LSD_{0.05}$	15.7	9.6	6.5	14.8	8.5	10.9	0.7	14.8
SEM (Prob)	4.81^{ns}	2.98^{ns}	2.00^{ns}	4.52^{ns}	2.72^{ns}	3.53^{ns}	0.23^{ns}	4.76^{ns}
N rate effect with S_{Ret}								
0 mean	60.4	19.5	3.3	83.2	57.9	20.9	2.7	81.5
50 mean	39.7	16.0	3.5	59.2	28.8	13.3	6.5	48.6
100 mean	36.4	12.8	3.4	52.6	33.3	15.5	2.5	51.3
$LSD_{0.05}$	10.4	8.7	1.5	12.5	10.8	8.0	7.5	14.2
SEM (Prob)	3.40***	2.84^{ns}	0.50^{ns}	4.09***	3.64***	2.71^{ns}	2.52^{ns}	4.80***

^{z}NT = No-tillage, RT = Reverse tillage, S_{Rem} = Straw removed, S_{Ret} = Straw retained, 0, 50 and 100 kg N ha^{-1}.

•, *, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Previous research under long-term no-tillage (NT) management has shown higher amounts of available P in the surface thin layer (0 to 5 cm or less) under NT than CT (Eckert 1985; Weil et al., 1988; Karlen, 1991; Ismail et al., 1994; Selles et al., 1997; Selles et al., 1999; Lupwayi et al., 2006, Mathers & Nash, 2009, Cade-Menun et al., 2010). Similarly, in our study, the amounts of extractable P in the surface 0-7.5 cm soil layer were greater under NT compared to RT, but the amounts of extractable P in the 7.5-15 and 15-20 cm layers were greater with RT compared to NT. The greater amounts of extractable p in the surface 0-7.5 cm layer under NT than RT were probably because of P "stratification", resulting in accumulation of more extractable P due to P application and from decomposition of crop residues retained on the soil surface under NT, as also suggested by Essington and Howard (2000). It is also possible that increased mixing by tillage under RT may have buried P-rich crop residue and soil into subsoil layers, resulting in increased mineralization of P from crop residue/soil organic matter, thus increasing extractable P content in the subsoil layers. Our findings suggest the importance of NT in maintaining higher concentration of readily plant-available P in soil near the surface where tillage is eliminated, and the need for additional P fertilization under NT because inorganic P at the soil surface under NT may not become fully available to the crop due to its relatively high immobility in the soil profile. Our findings also suggest the economic importance of occasional tillage (i.e., RT) in increasing the availability of extractable P which has accumulated at the soil surface under NT, by moving it into the subsoil layers where crop plant roots can intercept it.

The higher soil extractable P in S_{Ret} treatment than in S_{Rem} treatment in our study was probably due to the return of some P in crop residues in S_{Ret} treatment. This suggests the positive effect of returning crop residue in improving P fertility of soil and thus increasing potential for long-term sustainability of soil productivity, as most soils, especially Black Chernozem, in this region inherently contain insufficient amounts of available P for optimum crop growth and yield. Extractable P of soil in our study decreased significantly with application of N fertilizer, most likely due to the higher crop yield from N application, and subsequently higher P uptake in the seed which was removed from the field, leaving less residual P in soil.

In summary, our findings do not show any negative impact of occasional tillage of long-term NT on soil fertility.

Acknowledgements

The authors thank K Strukoff for technical help and D. Leach for statistical analysis.

References

Baan, C. D., Grevers, M. C. J., & Schoenau, J. J. (2009). Effects of a single cycle of tillage on long-term no-till prairie soils. *Canadian Journal of Soil Science,* 89, 521-530. http://dx.doi.org/10.4141/cjss08041

Cade-Menun, B., Carter, M. R., James, D. C., & Liu, C. W. (2010). Phosphorous forms and chemistry in the soil profile under long-term conservation tillage: A phosphorous-31 nuclear magnetic resonance study.

Journal of Environmental Quality, 39, 1647-1656. http://dx.doi.org/10.2134/jeq2009.0491

Campbell, C. A., McConkey, B. G., Zentner, R. P., Dyck, F. B., Selles, F., & Curtin, D. (1996). Carbon sequestration in Brown Chernozem as affected by tillage and rotation. *Canadian Journal of Soil Science, 75*, 449-458. http://dx.doi.org/10.4141/cjss95-065

Campbell, C. A., Tessier, J. S. J., & Selles, F. (1988). Challenges and limitations to adoption of conservation tillage – soil organic matter, fertility, moisture and soil environment. In: *Land Degradation and Conservation Tillage. Proc. 34th Annual CSSS/AIC Meeting, AIC, Calgary, Alberta, Canada* (pp. 140-185).

Campbell, C. A., Thomas, A. G., Biederbeck, V. O., McConkey, B. G., Selles, F., Spurr, D., & Zentner, R. P. (1998). Converting from no-tillage to pre-seeding tillage: influence on weeds, spring wheat grain yields and N, soil quality. *Soil & Tillage Research, 46*, 175-185. http://dx.doi.org/10.1016/S0167-1987(98)00031-2

Campbell, C. A., Zentner, R. P., Janzen, H. H., & Bowren, K. E. (1990). *Crop rotation studies on the Canadian Prairies*. Canadian Government Publication Centre, Supply and Services Canada, Hull, Quebec, Canada. Publ. No. 184/E, p. 133.

Crozier, C. R., Naderman, G. C., Tucker, M. R., & Sugg, R. E. (1999). Nutrient and pH stratification with conventional and no-till management. *Communications in Soil Science and Plant Analysis, 30*, 65-74. http://dx.doi.org/10.1080/00103629909370184

Culley, J. L. B. (1993). Density and compressibility. In M. R. Carter (Ed.), *Soil sampling and methods of analysis.* Lewis Publishers, Boca Raton, FL, U.S.A.

Derksen, D. A., Lafond, G. P., Thomas, A. G., Loeppky, H. A., & Swanton, C. J. (1993). Impact of agronomic practices on weed communities – tillage systems. *Weed Science, 41*, 409-417.

Donald, W.W. (1990). Primary tillage for Foxtail barley (*Hordeum jubatum* L.) control. *Weed Technology*, 4, 318-321. http://www.jstor.org/stable/3987080

Eckert, D. J. (1985). Effects of reduced tillage on the distribution of soil pH and nutrients in soil profiles. *Journal of Fertilizer Issues, 2*, 86-90.

Essington, M. F., & Howard, D. D. (2000). Phosphorus availability and speciation in long-term no-till and disk-till soil. *Soil Science, 165*, 144-152. http://dx.doi.org/10.1097/00010694-200002000-00005

Ferguson, A. J. D., Pearson, M. J., & Reynolds, C. S. (1996). Eutrofication of natural water and toxic algal blooms. *Issues in Environmental Science and Technology, 5*, 27-41. http://dx.doi.org/10.1039/9781847550088-00027

Grant, C. A., & Lafond, G. P. (1994). The effects of tillage systems and crop rotations on soil chemical properties of a Black Chernozemic soil. *Canadian Journal of Soil Science, 74*, 301-306. http://dx.doi.org/10.4141/cjss94-042

Guillard, K., Griffin, G. F., Allinson, D. W., Yamartino, W. R., Rafey, M. M., & Pietrzyk, W. (1995). Nitrogen utilization of selected cropping systems in the U.S. Northeast II: Soil profile nitrate distribution and accumulation. *Agronomy Journal, 87*, 199-207. http://dx.doi.org/10.2134/agronj1995.00021962008700020011x

Irvine, B., Derkson, D., Moulin, A., McLaren, D., & Grant, C. (2003). Strategic tillage – Evolution or devolution of zero tillage? Retrived from http://www.umanitoba.ca/faculties/afs/MAC_proceedings/2003/pdf/irvine_strategic_tillage.pdf

Ismail, I., Blevins, R. L., & Frye, W. W. (1994). Long-term no-tillage effects on soil properties and continuous corn yields. *Soil Science Society of America Journal, 58*, 193-198. http://dx.doi.org/10.2136/sssaj1994.03615995005800010028x

Johnson, M. D., & Lowery, B. (1985). Effect of three conservation tillage practices on soil temperature and thermal properties. *Soil Science Society of America Journal, 49*, 1547-1552. http://dx.doi.org/10.2136/sssaj1985.03615995004900060043x

Jones, O. R., Allen, R. R., & Unger, P. W. (1990). Tillage systems and equipment for dryland farming. In: R.P. Singh, F. Parr and B.A. Stewart (Eds.), *Dryland Agriculture: Strategies for Sustainability*. Vol. 13. (pp 89-125). Springer-Verlag, New York, NY, U.S.A. http://dx.doi.org/10.1007/978-1-4613-8982-8_5

Jones, C., Miller, P., Engel, R., & Rick, T. (2009). *Strategies to stretch your phosphorous fertilizer dollar* [PowerPoint slides]. Retrieved from http://landresources.montana.edu/soilfertility/documents/PDF/pres/P%20Management_Judith%20Basin%202009.pdf

Karlen, D. L., Berry, E. C., Colvin, T. S., & Kanwar, R. S. (1991). Twelve-year tillage and rotation effects on yields and soil chemical properties in northeast Iowa. *Communications in Soil Science and Plant Analysis, 22*, 1985-2003. http://dx.doi.org/10.1080/00103629109368552

Lal, R., Logan, T. J., & Fausey, N. R. (1990). Long-term tillage effects on a Mollic Ochraqualf in north-west Ohio III. Soil nutrient profile. *Soil & Tillage Research, 15*, 371-382. http://dx.doi.org/10.1016/0167-1987(90)90110-Y

Larney, F. J., Bremer, E., Janzen, H. H., Johnston, A. M., & Lindwall, C. W. (1997). Changes in total, mineralizable and light fraction soil organic matter with cropping and tillage intensities in semiarid southern Alberta, Canada. *Soil & Tillage Research, 42*, 229-240. http://dx.doi.org/10.1016/S0167-1987(97)00011-1

Lupwayi, N. Z., Clayton, G. W., O'Donovan, J. T., Harker, K. N., Turkington, T. K., & Soon, Y. K. (2006). Soil nutrient stratification and uptake by wheat after seven years of conventional and zero tillage in the northern grain belt of Canada. *Canadian Journal of Soil Science, 86*, 767-778. http://dx.doi.org/10.4141/S06-010

Lessard, R., Rochette, P., Gregorich, E. G., Patty, E., & Desjardins, R. L. (1996). N_2O fluxes from manure amended soil under maize. *Journal of Environmental Quality*, 25, 1371-1377. http://dx.doi.org/10.2134/jeq1996.00472425002500060029x

Malhi, S. S., & Lemke R. (2007). Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and greenhouse gas emissions in the second 4-yr rotation cycle. *Soil & Tillage Research, 96*, 269-283. http://dx.doi.org/10.1016/j.still.2007.06.011

Malhi, S. S., & Nyborg, M. (1987). Influence of tillage on nitrate-N in soil. *Canadex – Tillage/Soil Fertility, December 1987*, Communications Branch, Agriculture Canada, Ottawa, Canada.

Malhi, S. S., & O'Sullivan, P. A. (1990). Soil temperature, moisture and compaction under zero and conventional tillage in central Alberta. *Soil & Tillage Research, 17*, 167-172. http://dx.doi.org/10.1016/0167-1987(90)90014-5

Malhi, S. S., Brandt, S., Ulrich, D., Lemke, R., & Gill, K. S. (2002). Accumulation and distribution of nitrate-N and extractable P in the soil profile under various alternative cropping systems. *Journal of Plant Nutrition, 25*, 2499-2520. http://dx.doi.org/10.1081/PLN-120014709

Malhi, S. S., Brandt, S. A., Lemke, R., Moulin, A. P., & Zentner, R. P. (2009). Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and N and P balance in the Canadian Prairie. *Nutrient Cycling in Agroecosystems, 84*, 1-22. http://dx.doi.org/10.1007/s10705-008-9220-0

Dyck, M., Malhi, S. S., Nyborg, M., & Puurveen, D. (2015). Effects of short-term tillage of a long-term no-till land on crop yield and nutrient uptake in two contrasting soil types. *Sustainable Agriculture Research,* In Review.

Malhi, S. S., Harapiak, J. T., Nyborg, M., & Flore, N. A. (1991). Soil chemical properties after long-term N fertilization of bromegrass: Nitrogen rate. *Communications in Soil Science and Plant Analysis, 22*, 1447-1458. http://dx.doi.org/10.1080/00103629109368505

Malhi, S. S., Lemke, R., Wang, Z. H., & Chhabra, B. S. (2006). Influence of tillage and crop residue management on crop yield, greenhouse gas emissions and soil quality. *Soil & Tillage Research, 90*, 171-183. http://dx.doi.org/10.1016/j.still.2005.09.001

Malhi, S. S., Mumey, G., O'Sullivan, P. A., & Harker, K. N. (1988). An economic comparison of barley production under zero and conventional tillage. *Soil & Tillage Research, 11*, 159-166. http://dx.doi.org/10.1016/0167-1987(88)90023-2

Malhi, S. S., Nyborg, M., Goddard, T., & Puurveen, D. (2010). Long-term tillage, straw and N rate effects on quantity and quality of organic C and N in a Gray Luvisol soil. *Nutrient Cycling in Agroecosystems, 90*, 1-20. http://dx.doi.org/10.1007/s10705-010-9399-8

Malhi, S. S., Nyborg, M., Goddard, T., & Puurveen, D. (2011a). Long-term tillage, straw management and N fertilization effects on quantity and quality of organic C and N in a Black Chernozem soil. *Nutrient Cycling in Agroecosystems, 90*, 227-241. http://dx.doi.org/10.1007/s10705-011-9424-6

Malhi, S. S., Nyborg, M., Goddard, T., & Puurveen, D. (2011b). Long-term tillage, straw and N rate effects on some chemical properties in two contrasting soil types. *Nutrient Cycling in Agroecosystems, 90*, 133-146. http://dx.doi.org/10.1007/s10705-010-9417-x

Malhi, S. S., Nyborg, M., Goddard, T. & Puurveen, D. (2011c). Influence of long-term tillage, straw and N fertilizer management on crop yield, N uptake, and N balance sheet in two contrasting soil types. *Communications in Soil Science and Plant Analysis, 42*, 2548-2560. http://dx.doi.org/10.1080/00103624.2011.609262

Malhi, S. S., Nyborg, M., & Solberg, E. D. (1996). Influence of source, method of placement and simulated rainfall on the recovery of ^{15}N-labelled fertilizers under zero tillage. *Canadian Journal of Soil Science, 76*, 93-100. http://dx.doi.org/10.4141/cjss96-013

Mathers, N. J., & Nash, D. M. (2009). Effects of tillage practices on soil and water phosphorous and nitrogen fractions in a Chromosol at Rutherglen in Victoria, Australia. *Australian Journal of Soil Research, 47*, 46-59. http://dx.doi.org/10.1071/SR08106

McGill, W. B., Dormaar, J. F., & Reinl-Dwyer, E. (1988). New perspectives on soil organic matter quality, quantity, and dynamics on the Canadian Prairies. In *Proc. Canadian Society of Soil Science and Canadian Society of Extension Joint Symposium, Land degradation: Assessment and insight into a western Canadian problem. August 23, 1988, Calgary, Alberta, Canada* (pp. 30-48). Agricultural Institute of Canada.

Meek, B., Graham, L., & Donovan, T. (1982). Long-term effects of manure on soil nitrogen, phosphorus, potassium, sodium, organic matter and water infiltration rate. *Soil Science Society of America Journal, 44*, 1014-1019. http://dx.doi.org/10.2136/sssaj1982.03615995004600050025x

Mooleki, S. P., Malhi, S. S., Lemke, R., Schoenau, J. J., Lafond, G., Brandt, S., … May, W. E. (2010). Effect of nitrogen management, and phosphorus placement on wheat production in Saskatchewan. *Canadian Journal of Plant Science, 90*, 319-337. http://dx.doi.org/10.4141/CJPS09075

Nuttall, W. F., Bowren, K. E., & Campbell, C. A. (1986). Crop residue management practices, and N and P fertilizer effects on crop response and on some soil physical and chemical properties of a Black Chernozem over 25 years in a continuous wheat rotation. *Canadian Journal of Soil Science, 66*, 159-171. http://dx.doi.org/10.4141/cjss86-016

Nyborg, M., & Malhi, S. S. (1989). Effect of zero and conventional tillage on barley yield and nitrate-N content, moisture and temperature of soil in north-central Alberta. *Soil & Tillage Research, 15*, 1-9. http://dx.doi.org/10.1016/0167-1987(89)90059-7

Nyborg, M., Solberg, E. D., Malhi, S. S., & Izaurralde, R. C. (1995). Fertilizer N, crop residue, and tillage after soil C and N content in a decade. In R. Lal, J. Kimble, E. Levine & B. A. Stewart (Eds.), *Advances in Soil Science: Soil management and greenhouse effect*. (pp. 93-99). Lewis Publishers, CRC Press, Boca Raton, FL, U.S.A.

Qian, P., Schoenau, J. J., & Karamanos, R. E. (1994). Simultaneous extraction of phosphorus and potassium with a new soil test: A modified Kelowna extraction. *Communications in Soil Science and Plant Analysis, 25*, 627-635. http://dx.doi.org/10.1080/00103629409369068

SAS Institute. (2004). *SAS product documentation. Version 8*. SAS Inst., Cary, NC, U.S.A. Retrieved from http://support.sas.com/documentation/onlinedoc/index.html (verified 17 July 2009).

Selles, F., Karamanos, R. E., & Bowren, K. E. (1984). Changes in natural 15N abundance of soils associated with tillage practices. *Canadian Journal of Soil Science, 54*, 345-354. http://dx.doi.org/10.4141/cjss84-036

Selles, F., Kochhann, R. A., Denardin, J. E., Zentner, R. P., & Faganello, A. (1997). Distribution of phosphorous fractions in a Brazilian Oxisol under different tillage systems. *Soil & Tillage Research, 44*, 23-34. http://dx.doi.org/10.1016/S0167-1987(97)00026-3

Selles, F., McConkey, B. G., & Campbell, C. A. (1999). Distribution and forms of P under cultivator- and zero-tillage for continuous- and fallow-wheat cropping systems in the semi-arid Canadian Prairies. *Soil* *and Tillage Research, 51*, 47-59. http://dx.doi.org/10.1016/S0167-1987(99)00027-6

Singh, H., & Singh, K. P. (1994). Nitrogen and phosphorus availability and mineralization in dryland reduced tillage cultivation – effects of residue placement and chemical fertilizer. *Soil Biology & Biochemistry, 26*, 695-702. http://dx.doi.org/10.1016/0038-0717(94)90261-5

Technicon Industrial Systems. (1973a). *Ammonium in water and waste water. Industrial Method No. 90-70W-B. Revised January 1978*. Technicon Industrial Systems, Tarrytown, NY, U.S.A.

Technicon Industrial Systems. (1973b). *Nitrate in water and waste water. Industrial Method No. 100-70W-B. Revised January 1978*. Technicon Industrial Systems, Tarrytown, NY, U.S.A.

Technicon Industrial Systems. (1977). *Industrial/simultaneous determination of nitrogen and/or phosphorus in BD acid digests*. Industrial method no. 334-74W/Bt. Tarrytown, NY, U.S.A.

Tessier, S., Peru, M., Dyck, F. B., Zentner, R. P., & Campbell, C. A. (1990). Conservation tillage for spring wheat production in semiarid Saskatchewan. *Soil & Tillage Research, 18*, 73-79. http://dx.doi.org/10.1016/0167-1987(90)90094-T

Vanderbygaart, A. J., & Kay, B. D. (2004). Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario, Canada. *Soil Science Society of America Journal, 68*, 1394-1402. http://dx.doi.org/10.2136/sssaj2004.1394

Vasconcelos, E., Cabral, F., & Cordovil, C. M. D. (1997). Effect of solid phase from pig slurry on soil chemical characteristics, nitrate leaching composition and yield of wheat. *Journal of Plant Nutrition, 20*, 939-952. http://dx.doi.org/10.1080/01904169709365307

Weil, R. R., Benedetto, P. W., Sikora, L. J., & Bandel, V. A. (1988). Influence of tillage practices on phosphorus distribution and forms in three Ultisols. *Agronomy Journal, 80*, 503-509. http://dx.doi.org/10.2134/agronj1988.00021962008000030022x

Wolfe, A. M., & Eckert, D. J. (1999). Crop sequence and surface residue effects on the performance of no-till corn grown on a poorly drained soil. *Agronomy Journal, 91*, 363-367. http://dx.doi.org/10.2134/agronj1999.00021962009100030002x

Yang, X. M., & Kay, B. D. (2001). Rotation and tillage effects on soil organic carbon sequestration in a Typic Hapludalf in southern Ontario. *Soil & Tillage Research, 59*, 107-114. http://dx.doi.org/10.1016/S0167-1987(01)00162-3

Yuan, X., Tong, Y., Yang, X., Li, X., & Zhang, F. (2000). Effect of organic manure on soil nitrate accumulation. *Soil Environmental Science, 9*, 197-200.

Zhang, W. L., Tian, Z. X., Zhang, N., & Li, X. O. (1996). Nitrate pollution of ground water in northern China. *Agriculture, Ecosystems & Environment, 59*, 223-231. http://dx.doi.org/10.1016/0167-8809(96)01052-3

Zibilske, L. M., Bradford, J. M., & Smart, J. R. (2002). Conservation tillage induced changes in organic carbon, total nitrogen and available phosphorus in a semi-arid alkaline subtropical soil. *Soil & Tillage Research, 66*, 153-163. http://dx.doi.org/10.1016/S0167-1987(02)00023-5