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Long-Term Trends in Nitrous Oxide Emissions, Soil Nitrogen, and Crop Yields of Till and No-Till Cropping Systems

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ABSTRACT

No-till cropping can increase soil C stocks and aggregation but patterns of long-term changes in N_2O emissions, soil N availability, and crop yields still need to be resolved. We measured soil C accumulation, aggregation, soil water, N_2O emissions, soil inorganic N, and crop yields in till and no-till corn–soybean–wheat rotations between 1989 and 2002 in southwestern Michigan and investigated whether tillage effects varied over time or by crop. Mean annual NO_3^- concentrations in no-till were significantly less than in conventional till in three of six corn years and during one year of wheat production. Yields were similar in each system for all 14 years but three, during which yields were higher in no-till, indicating that lower soil NO_3^- concentrations did not result in lower yields. Carbon accumulated in no-till soils at a rate of 26 g C m^{-2} yr^{-1} over 12 years at the 0- to 5-cm soil depth. Average nitrous oxide emissions were similar in till (3.27 ± 0.52 g N ha d^{-1}) and no-till (3.63 ± 0.53 g N ha d^{-1}) systems and were sufficient to offset 56 to 61% of the reduction in CO_2 equivalents associated with no-till C sequestration. After controlling for rotation and environmental effects by normalizing treatment differences between till and no-till systems we found no significant trends in soil N, N_2O emissions, or yields through time. In our sandy loam soils, no-till cropping enhances C storage, aggregation, and associated environmental processes with no significant ecological or yield tradeoffs.

Soil organic matter (SOM) losses are rapid following initial tillage of undisturbed soils (Martel and Paul, 1974; Balesdent et al., 1988; Davidson and Ackerman, 1993). After 20 years, 20 to 40% or more of the original soil C may be lost (Davidson and Ackerman, 1993). Restoration of some portion of the 55 Pg C lost from arable soils globally is one of several short-term, high-impact options for stabilizing global CO_2 levels (Caldeira et al., 2004; Council for Agricultural Science and Technology, 2004; Lal, 2004). No-till cropping generally increases soil C stocks at an average annual rate of 30 to 60 g C m^{-2} yr^{-1} (Davidson and Ackerman, 1993; West and Post, 2002) and is thus a prominent agricultural CO_2 mitigation strategy. Use of no-till soil management has been steadily increasing during the past decade: between 1994 and 2004 the percentage of total U.S. cropland in no-till rose from 13.7 to 22.6%, or 9.5 million hectares (Conservation Technology Information Center, 2004). Many more hectares are suitable for no-till but its deployment has been limited in part by the perception that accelerated rates of N leaching and immobilization may reduce plant N availability and decrease yields (Martens, 2001). Further, studies have suggested that increases in N_2O emissions following conversion to no-till might offset some portion of the CO_2 mitigation, making the long-term global warming potential (GWP) of till and no-till systems similar (MacKenzie et al., 1997; Six et al., 2004).

Higher N_2O emissions in no-till than in conventionally tilled cropping systems have been frequently reported (MacKenzie et al., 1997; Ball et al., 1999; Baggs et al., 2003), although some studies have found lower emissions in no-till soils or no difference between tillage systems (Robertson et al., 2000; Elmi et al., 2003), demonstrating the potential for responses to vary across cropping systems and soil types. In a recent review, Six et al. (2004) analyzed N_2O emissions data in a linear mixed-effect model and concluded that differences in N_2O fluxes between till and no-till change over time. In humid ecosystems, N_2O fluxes appear to be higher in no-till during the first decade but after 20 years no-till emissions appear to be lower. In an assessment of the effect of potential European land-use changes on non-CO_2 greenhouse gases, Smith et al. (2001) calculated that eliminating tillage on all potential no-till lands could result in an increase in N_2O emissions equivalent to 20.5 Tg C yr^{-1}. The potential mechanisms explaining this include decreased O_2 availability associated with increased bulk density and water-filled pore space, and increased soil organic matter decomposition in no-till soils (Linn and Doran, 1984; Guzha, 2004); alterations to the synchrony between plant N uptake and N availability (Six et al., 2004); and litter C accumulation at the soil surface (Arshad et al., 1999; Baggs et al., 2003).

Along with soil surface N_2O emissions, soil inorganic N cycling frequently changes following conversion to no-till and these changes may decrease yields (Rice et al., 1986; Niehues et al., 2004). Application of urea ammonium nitrate (UAN) fertilizer to the soil surface results in greater ammonia volatilization in no-till than in conventional till systems, where fertilizer is incorporated into the soil (Keller and Mengel, 1986; Fox and Piekielek, 1993). Along with volatilization, immobilization of N in surface residues and decreased N mineralization rates can limit N availability and potentially decrease yields in no-till (Kaspar et al., 1987; Ismail et al., 1994). Reduced mineralization rates and other problems (e.g., delayed and uneven germination) due to cool and water-saturated soils may be particularly detrimental to yields in the northern Corn Belt (Kaspar et al., 1987; Vetsch and Randall, 2000) and on

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Abbreviations: GWP, global warming potential; KBS LTER, W.K. Kellogg Biological Station Long-Term Ecological Research Project; MWD, soil aggregate mean weight diameter.

fine-textured soils (Vyn and Raimbault, 1993; Beyaert et al., 2002).

As with N_2O emissions, soil N cycling and crop productivity responses to no-till may change over time. Vyn and Raimbault (1993) found that corn yields increased in no-till during the first eight years and then declined. Other studies have found that no-till has no effect on yields (Mehdi et al., 1999; Beyaert et al., 2002), decreases yields initially before a yield recovery (Rice et al., 1986), or is related to annual environmental conditions or other factors independent of time since initiation (Ismail et al., 1994). Additional data are needed describing long-term annual trends in soil N cycling, yields and, particularly, N_2O emissions to develop predictive models for long-term no-till cropping systems.

Our objectives in this study are to (i) determine the effects of long-term no-till soil management in a corn–soybean–wheat rotation on C sequestration and the extent to which increases in N_2O flux can offset the GWP impact of enhanced C storage; (ii) determine whether changes in soil water content, N availability, and yields occur that could limit the deployment of no-till in southwestern Michigan; and (iii) investigate whether responses to no-till vary over 14 years of no-till management. In a previous study Robertson et al. (2000) reported no difference in the mean annual N_2O flux from these treatments between 1991 and 1999. Here, we investigate interannual patterns of N_2O emissions, yield, and other ecosystem properties to better understand the effects of no-till management between 1989 and 2002. Our hypothesis is that N_2O emissions will initially be higher in no-till soils and then decrease over time, and that soil inorganic N concentrations will be lower in no-till soils, potentially lowering yields of corn and wheat in these northern Corn Belt soils.

MATERIALS AND METHODS

Experimental Site

Experimental plots were located at the W.K. Kellogg Biological Station Long-Term Ecological Research (KBS LTER) site (http://lter.kbs.msu.edu; verified 9 Dec. 2005) in southwestern Michigan (85°24′ W, 42°24′ N; 920 mm yr^{-1} precipitation). Tillage treatments were established in 1989 in six replicated 1-ha plots organized in a randomized complete block design. Soils are Kalamazoo (fine-loamy, mixed, semiactive, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, active, mesic Typic Hapludalfs), developed on glacial outwash (Crum and Collins, 1995). The two series co-occur in all ecosystems and differ mainly in their Ap horizon texture, though variation within a series can be as great as variation between a series (Robertson et al., 1997).

Agronomic Protocols

The crop rotation before 1995 consisted of corn followed by soybean. In 1995, wheat was planted after soybean, initiating a corn–soybean–wheat rotation. Primary tillage consisted of spring moldboard plowing from 1989 to 1998 and spring chisel plowing from 1999 to 2002. Secondary tillage consisted of disking before wheat planting, field conditioner before soybean and corn planting, and inter-row cultivation for soybean and corn. Fertilizer applications were identical in both tillage systems. Detailed information about annual applications can be found on the KBS LTER website (http://lter.kbs.msu.edu). Side-dress NH_4NO_3 fertilizer was broadcast over corn in 1989 (123 kg N ha^{-1}), 1991 (123 kg N ha^{-1}), and 1993 (84 kg N ha^{-1}). In 1996 and 1999, corn received 28 kg N ha^{-1} urea ammonium nitrate (28%) at planting and an additional 135 kg side-dress N ha^{-1} as NH_4NO_3. In 2002, corn received 29 kg N ha^{-1} starter fertilizer and an additional 124 kg side-dress N ha^{-1}. In April 1995 and 1998 wheat received 56 kg side-dress N ha^{-1} broadcast as NH_4NO_3. The 2001 wheat crop received 71 kg side-dress N as urea ammonium nitrate. No N fertilizer was applied to soybean. Lime, N, P, and K were applied as needed according to Michigan State University recommendations.

Soil Sampling and Storage

Soil samples for aggregate size distribution and total C and N analysis were collected from five sites within each plot in June and July, 2001. At each of the five sample locations, two subsamples with a diameter of 7.6 cm were taken to a depth of 5 cm by gently hammering a PVC core into the ground to minimize compression and slicing of aggregates. One of the subsamples at each location was taken in the row and the other between the rows. All ten subsamples from each plot were combined to produce one representative sample. Four separate samples for bulk density analysis were taken at the same time as those for aggregate analysis, using an 8.0-cm-diameter root corer.

Field-moist soil samples were put into a cooler (4°C) before being broken along natural fracture planes and passed through an 8-mm sieve within 72 h of sampling. After sieving, soils were air-dried in paper bags at 20°C before storage in plastic bags. Care was taken throughout the study to minimize disturbance of the samples that might influence aggregate structure. Total soil C and N concentrations were determined by dry combustion methods in a CHNS analyzer (ECS 4010; Costech Analytical Technologies, Valencia CA).

Soil Aggregation

Aggregate distribution was determined on triplicate 35-g air-dried soil samples by hand-sieving in water through a series of sieves (2000 μm, 250 μm, and 53 μm; Cambardella and Elliott, 1993; Six et al., 1998; Grandy and Robertson, 2006). Soil was submerged for 5 min on the surface of the 2000-μm sieve which was then moved up and down over 2 min with a stroke length of 3 cm for 50 strokes. Sieving was repeated on the 250-μm (50 strokes) and 53-μm (30 strokes) sieves using the soil plus water that passed through the next larger sieve. Aggregates remaining on each sieve were dried at 60°C.

Mean weight diameter (MWD) of sand-free aggregates was determined by calculating the sum of the products of the mean diameter of each size fraction and the proportion of the total sample weight in that fraction (Kemper and Rosenau, 1986).

Nitrous Oxide Gas Emissions

Nitrous oxide measurements were made using 15 600 cm^{-3} static chambers (Livingston and Hutchinson, 1995) at weekly to monthly intervals when soils were not frozen (Robertson et al., 2000). Single chambers were located in four of the six replicates of each treatment. Chamber lids were placed on semi-permanent aluminum bases removed only for cropping activities and accumulated headspace sampled four times over 120 min. All chambers were sampled on the same dates between 1991 and 2002, although no data are available for 1995. Samples were stored in 3-mL crimp-top vials and analyzed in the laboratory for N_2O with the flux for each chamber calculated as the linear portion of the gas accumulation curve for that chamber. Nitrous oxide was analyzed by gas chromatography using a ^{63}Ni electron capture detector (ECD).

Inorganic Soil Nitrogen

Soil NH_4^+ and NO_3^- were extracted with 1 *M* KCl monthly from 1991–1995, and twice per month from 1996–2002 during the growing season (otherwise once per month) from triplicate, field-moist, 10-g soil samples using a 1:10 soil to extractant ratio. Soil slurries were shaken for 1 min, left to equilibrate overnight, and re-shaken >1 h before filtering. Extracts were filtered with a syringe filter using a 1-μm glass fiber filter. Filtrates were stored in 7-mL scintillation vials and frozen until analysis for NH_4^+ and NO_3^-. Both analyses were performed on an Alpkem 3550 Flow Injector Analyzer (OI Analytical, College Station, TX) using colorimetric techniques (Robertson et al., 1999).

Global Warming Potential

Global warming potential (GWP) calculations were made for soil C accumulation in no-till relative to till between 1989 and 2001 and N_2O emissions from both tillage systems. The GWP for soil C accumulation in no-till was calculated according to Robertson et al. (2000) as follows:

$$X \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1} = \frac{(x_1 - x_2) \text{ kg C}}{\text{m}^2\, x_3 \text{ yr}} \times \frac{44 \text{ kg CO}_2}{12 \text{ kg C}} \times \frac{10^3 \text{ g CO}_2}{1 \text{ kg CO}_2}$$

where x_1 = soil C in no-till (kg C m^{-2}), x_2 = soil C in conventional till (kg C m^{-2}), and x_3 = years (yr) of accumulation. The GWP calculations for N_2O used an IPCC 20-yr time horizon factor of 280 for converting N_2O to CO_2 equivalents (Intergovernmental Panel on Climate Change, 2001):

$$X \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1} = \frac{x_1 \text{ g N}_2\text{O-N}}{\text{ha d}} \times \frac{44 \text{ g N}_2\text{O}}{28 \text{ g N}_2\text{O-N}} \times \frac{365 \text{ d}}{1 \text{ yr}} \times \frac{1 \text{ ha}}{10^4 \text{ m}^2} \times \frac{280 \text{ g CO}_2}{1 \text{ g N}_2\text{O}}$$

where x_1 = average daily N_2O-N emission rate (g N ha^{-1} d^{-1}).

Statistical Analysis

Tillage effects were analyzed by Proc Mixed (Version 8.2; SAS Institute, 1999) using a randomized complete block design analysis of variance (ANOVA) with repeated measures. Year and tillage treatments were considered fixed effects. Where significant treatment-by-year interactions occurred, results were sliced to determine whether treatment means significantly differed within individual years. Additionally, to determine trends in N_2O flux, soil inorganic N, and crop yields over time, differences between treatments within each block and year were normalized to the overall mean for that year:

$$\text{normalized percent difference} = \{[(Y_c - Y_n)/Y_{annual}] \times 100\}$$

where Y_c and Y_n are the annual mean for each block within a year for conventional and no-till, respectively, and Y_{annual} is the overall mean for that year, averaged across treatments. Regression analysis was used to determine whether there were trends in the response of till relative to no-till sites across crops and years, and also whether trends differed by crop. By normalizing the data before the regression analysis rather than using absolute differences we were able to isolate the relative effect of no-till over time and control for factors, such as the use of fertilizer or climatic differences, that might cause interannual variation in the magnitude of response in both treatments. The normalized differences were also analyzed by ANOVA using Proc Mixed with year as the fixed effect. Where there were significant year effects, indicating that the normalized difference varied with year, mean separation and rankings were performed using a Tukey's test with the PDMix800 Algorithm (Saxton, 2003).

RESULTS

Soil Properties

In 2001, 12 years after the adoption of no-till, soil aggregate MWD was 55% higher in no-till soils and there was an additional 310 g C m^{-2} to a depth of 5 cm (Table 1). This change over 12 years represents an annual C increase of 26 g C m^{-2} yr^{-1}. No bulk density differences were detected between the two treatments (Table 1).

There was a significant treatment-by-year interaction ($P < 0.05$) for gravimetric soil water content (Fig. 1). Soil water content was significantly greater in no-till than till in 2000 but in all other years there was no significant difference in soil water content between the two treatments. Regression analysis of the normalized difference between till and no-till treatments found no trend for soil water content across all years or for particular crops.

There was a significant treatment-by-year interaction ($P < 0.05$) for soil NO_3^- concentrations (Fig. 2) indicating that the effects of tillage differed by year. No-till reduced NO_3^- concentrations in 1991 (corn, 80%), 1996 (corn, 29%), 1999 (corn, 41%), and 2001 (wheat, 28%). There was not a significant linear trend in NO_3^- concentrations over all years, although there was a significant positive relationship between time and the normalized NO_3^- difference during wheat years [normalized NO_3^- difference = −15 650 + 7.84(year); r^2 = 0.44; n = 3]. This suggests that over 1995, 1998, and 2001 soil NO_3^- concentrations declined in no-till wheat plots relative to tilled plots. Mean separation showed that these three points were statistically equal and that 1991 was different from the other years because of higher NO_3^- concentrations in tilled soils.

Table 1. No-till soil management effects on soil aggregation, bulk density, and C sequestration in 2001 after 12 years at the W.K. Kellogg Biological Station Long-Term Ecological Research (KBS LTER) site.†

	Aggregate MWD‡	Bulk density	Organic C	ΔC§
	mm	g cm^{-3}	kg m^{-2}	g m^{-2} yr^{-1}
Conventional till	1.32 (0.14)*	1.37 (0.01)	0.69 (0.04)*	0
No till	2.04 (0.11)	1.36 (0.03)	1.00 (0.04)	26

* Significant at the 0.05 probability level.
† 0- to 5-cm sampling depth.
‡ Mean weight diameter.
§ Robertson et al. (2000) reported a C accumulation rate of 30 g C m^{-2} to 7 cm.

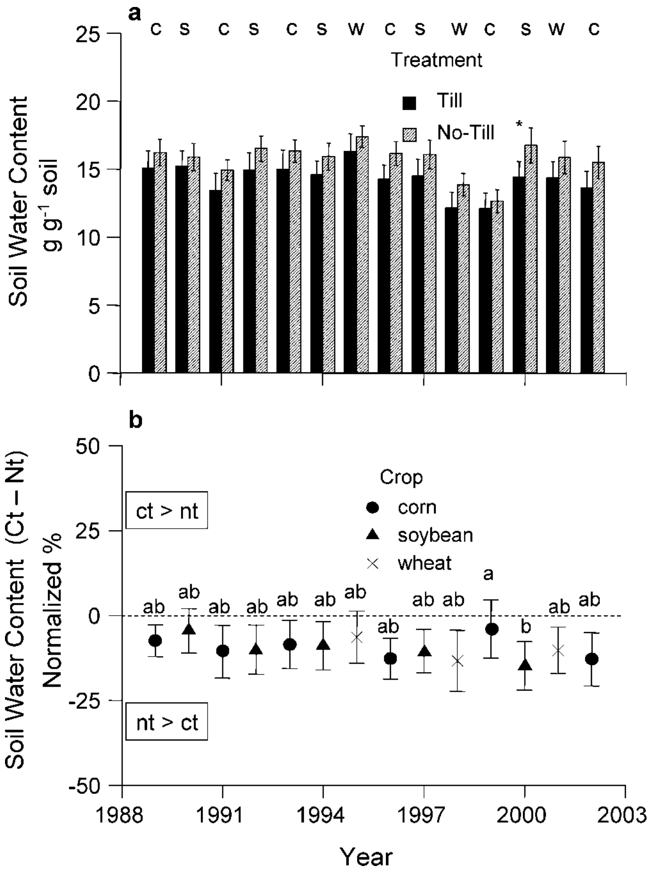

Fig. 1. (a) Gravimetric soil water content in till and no-till treatments between 1989 and 2002. Letters indicate the crop harvested in that year: c, corn; s, soybean; w, wheat. * Indicates statistically different responses within a year ($P < 0.05$) determined by slicing of the treatment by year interaction. (b) Difference between conventional till (Ct) and no-till (Nt) normalized by the overall mean soil water content for that year. Points greater than zero indicate a till response greater than a no-till response. Year means were significantly different ($P < 0.05$) and separated using Tukey's test. Linear regression analysis showed no trends in soil water concentration ($P < 0.05$) across all crops and years or for specific crops over time.

Response of soil NH_4^+ concentration to no-till also varied by year ($P < 0.05$; Fig. 3). The NH_4^+ concentrations were higher in tilled sites in 1991 (corn) and 2002 (corn) and no-till sites in 2000 (soybean). Linear regression showed that there was not a significant trend in NH_4^+ concentrations across all the crops and years and there were no significant trends for individual crops. Mean separation of the normalized difference by year showed the potential for inter-annual variability in the response to tillage but also showed no consistent trends by crop.

Nitrous Oxide Emissions and Global Warming Potential

There was no significant difference in N_2O emissions between tillage treatments averaged across years (conventional till = 3.27 ± 0.52; no-till = 3.63 ± 0.53 g ha^{-1} d^{-1}), but there was a significant year by treatment interaction (Fig. 4), with higher emissions occurring in no-till plots in 1991 (corn, 300%) and 2000 (soybean, 300%). Linear regression showed that there was no significant relationship between time and the normalized difference in N_2O flux across years and crops, but indicated that for the soybean crop N_2O emissions increased in no-till plots relative to till plots over four growing seasons between 1992 and 2000 [normalized N_2O difference = 31 210 − 15.7 (year); r^2 = 0.48; n = 4 yr]. Tukey's test ($P < 0.05$) showed that normalized differences in N_2O emissions were similar across years. In the no-till system C storage between 1989 and 2001 reduced soil CO_2 fluxes by 95 g CO_2 m^{-2} yr^{-1}, but 56 to 61% of that mitigation was offset by N_2O emissions of 53 to 58 g CO_2 equivalents m^{-2} yr^{-1} (Table 2).

Crop Yields

There was a significant ($P < 0.05$) treatment by year interaction for crop yields (Fig. 5). Crop yields were significantly greater in no-till sites in 1992 (soybean), 1996 (corn), and 1997 (soybean). There was not a sig-

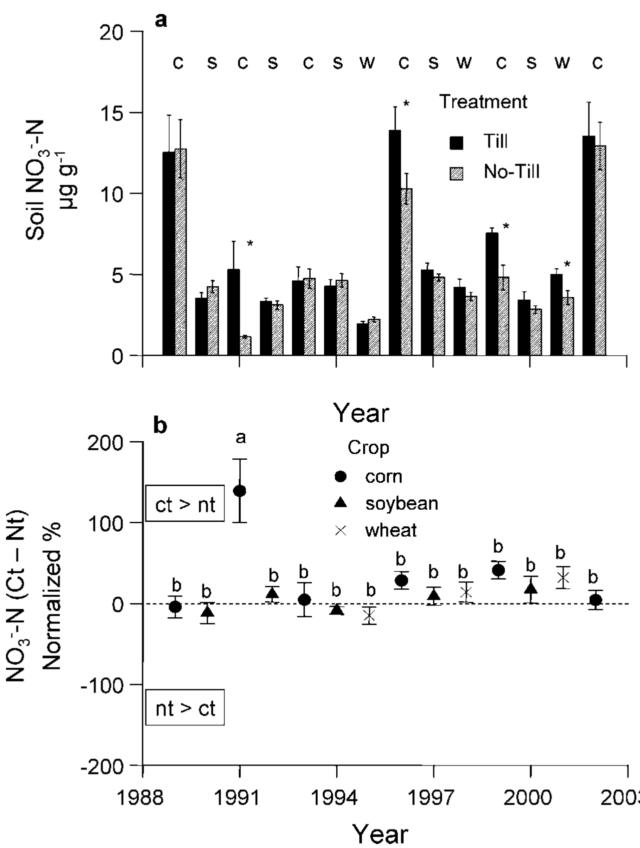

Fig. 2. (a) Soil NO_3^- concentration in till and no-till treatments between 1989 and 2002. Letters indicate the crop harvested in that year: c, corn; s, soybean; w, wheat. *Indicates statistically different responses within a year ($P < 0.05$) determined by slicing of the treatment by year interaction. (b) Difference between conventional till (Ct) and no-till (Nt) normalized by the overall mean NO_3^- concentration for that year. Points greater than zero indicate a till response greater than a no-till response. Year means were significantly different ($P < 0.05$) and separated using Tukey's test. Linear regression analysis showed no trend in NO_3^- concentration ($P < 0.05$) over across all crops and years; NO_3^- concentrations in wheat significantly increased in till relative to no-till over time [normalized NO_3^- difference = −15 650 + 7.84 (year); r^2 = 0.44; n = 3 yr]. Mean ± SE.

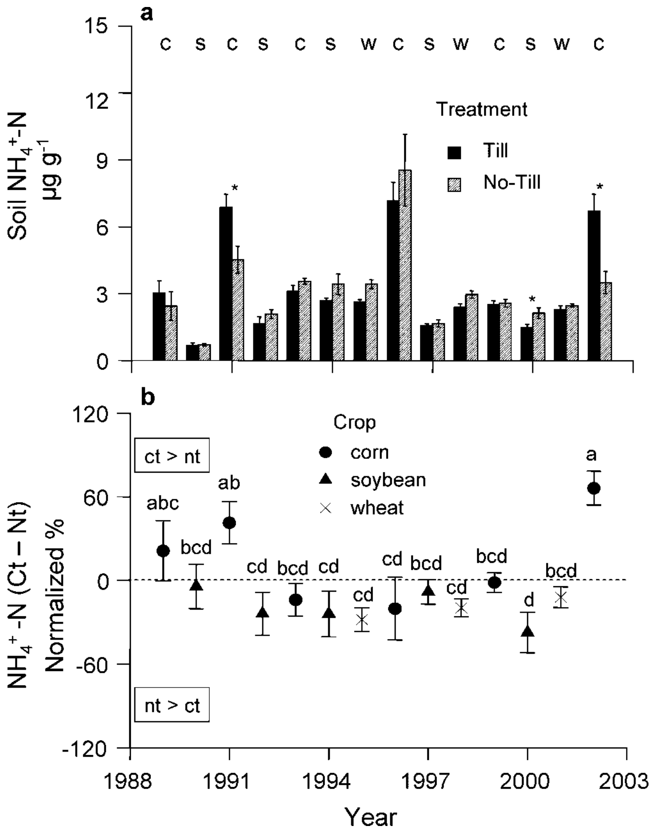

Fig. 3. (a) Soil NH_4^+ concentrations in till and no-till treatments between 1989 and 2002. Letters indicate the crop harvested in that year: c, corn; s, soybean; w, wheat. * Indicates statistically different responses within a year ($P < 0.05$) determined by slicing of the treatment by year interaction. (b) Difference between conventional till (Ct) and no-till (Nt) normalized by the overall mean NH_4^+ concentration for that year. Points greater than zero indicate a till response greater than a no-till response. Year means were significantly different ($P < 0.05$) and separated using Tukey's test. Linear regression analysis showed no trends in soil NH_4^+ concentration ($P < 0.05$) across all crops and years or for specific crops over time.

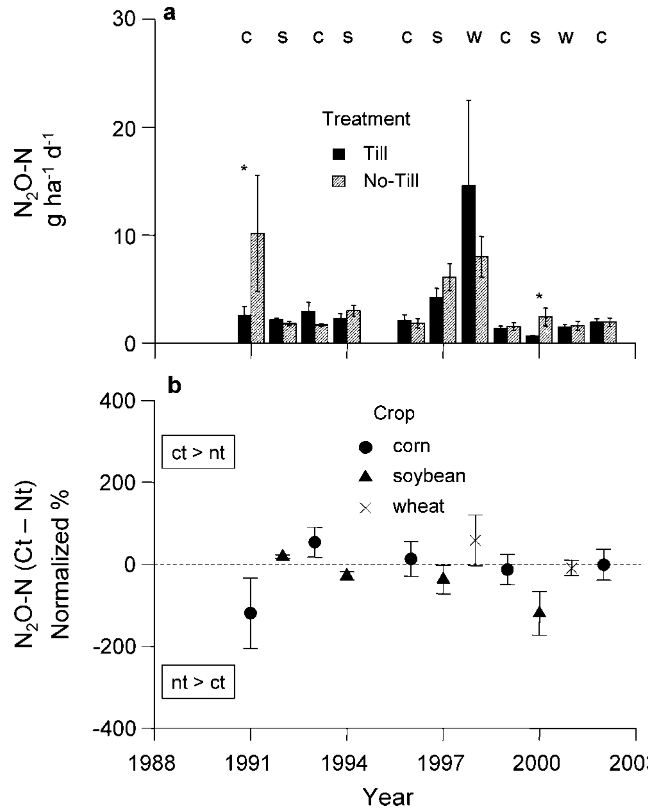

Fig. 4. (a) Soil N_2O emissions in till and no-till treatments between 1991 and 2002 (no data available for 1995). Letters indicate the crop harvested in that year: c, corn; s, soybean; w, wheat. * Indicates statistically different responses within a year ($P < 0.05$) determined by slicing of the treatment by year interaction. (b) Difference between conventional till (Ct) and no-till (Nt) normalized by the overall mean N_2O emissions for that year. Points greater than zero indicate a till response greater than a no-till response. There was no detectable difference between years based on a Tukey's test. Linear regression analysis showed no trend in N_2O emissions ($P < 0.05$) across all crops and years; emissions from soybean significantly increased in till relative to no-till over time [normalized N_2O difference = 31 210 − 15.7 (year); $r^2 = 0.48$; $n = 4$ yr]. Mean ± SE.

nificant linear relationship between crop yield and time across years. There was a significant positive relationship between time and wheat yields in no-till relative to conventional till [normalized yield difference = −5980 + 3.00(year); $P < 0.05$; $r^2 = 0.40$; $n = 3$ yr] for three growing years between 1995 and 2001. Mean separation indicated that the normalized mean difference was statistically equal for these three wheat years.

DISCUSSION

Nitrous Oxide and Global Warming Potential

Although we measured significantly greater N_2O fluxes from no-till plots in 1991 and 2000, such differences were not sustained throughout the study, and averaged across years there was not a significant effect of tillage (Fig. 4). Grant et al. (2004) predicted that across all of Canada adoption of no-till would reduce N_2O emissions by an average of 17%, but in eastern Canada greater precipitation and soil water-filled pore space would increase N_2O emissions. Grant et al.'s predictions are consistent with Six et al. (2004) that in humid climates no-till systems will have higher N_2O emissions for a decade or more after conversion. MacKenzie et al. (1997) found in eastern Canada that no-till increased N_2O emissions from 33 to 95%. In Saskatchewan, Canada, Aulakh et al. (1984) found that no-till doubled N_2O fluxes.

Table 2. Global warming potential (GWP) contributions in CO_2 equivalents from soil C storage and N_2O emissions in conventional and no-till systems between 1991 and 2002 at the W.K. Kellogg Biological Station Long-Term Ecological Research (KBS LTER) site.

	CO_2 equivalents	
	Conventional till	No till
	g m^{-2} yr^{-1}	
Soil C storage†	0	−95
N_2O emissions‡	53	58
GWP (N_2O + CO_2)	53	−37

† 0- to 5-cm sampling depth.

‡ Nitrous oxide emissions were statistically equal in till (3.27 ± 0.52 g N ha d^{-1}) and no-till (3.63 ± 0.53 g N ha d^{-1}). The N_2O production thus offset between 56 and 61% of the CO_2 stabilization associated with soil C increases in no-till.

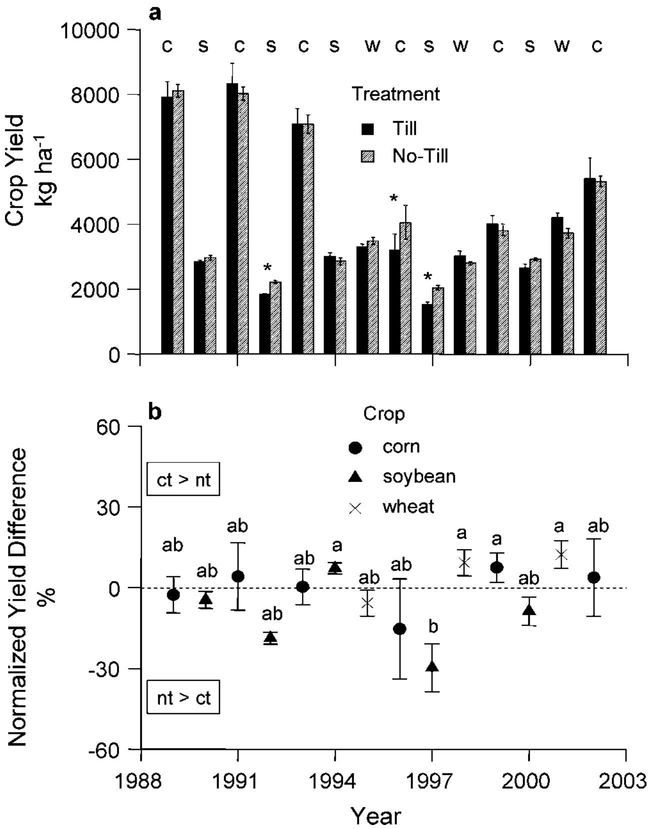

Fig. 5. (a) Crop yields in till and no-till treatments between 1989 and 2002. Letters indicate the crop harvested in that year: c, corn; s, soybean; w, wheat. * Indicates statistically different responses within a year ($P < 0.05$) determined by slicing of the treatment by year interaction. (b) Difference between conventional till (Ct) and no-till (Nt) normalized by the overall mean crop yield for that year. Points greater than zero indicate a till response greater than a no-till response. Year means were significantly different ($P < 0.05$) and separated using Tukey's test. Linear regression analysis showed no trend in crop yields ($P < 0.05$) across all crops and years; wheat yields significantly increased in till relative to no-till over time [normalized yield difference = −5980 + 3.00 (year); $r^2 = 0.40$; $n = 3$ yr]. Mean ± SE.

The mechanisms proposed to explain higher N_2O fluxes in no-till soils are related mainly to C accumulation at the soil surface, increased bulk density, and decreased crop yields altering the availability of C, N, and O_2 (Ball et al., 1999; Smith et al., 2001). While some no-till soils may be more susceptible to O_2 depletion following precipitation (Doran, 1980; Martens, 2001), the 50% greater aggregate MWD and statistically equal bulk density that we measured in no-till suggest that drainage and O_2 diffusion rates are similar or higher than those in tilled soils. Although our measurements were made 12 years after no-till conversion and may not represent soil structural dynamics during the first few years after adoption of no till, they are confirmed by measurements made on samples taken in 1995 (Six et al., 2000) showing statistically greater aggregation in no-till. Other studies have shown that no-till increases aggregation (Liebig et al., 2004) and that these changes can occur within the first few years after adoption (Rhoton, 2000) and have a positive impact on water dynamics and crop yields (Diaz-Zorita et al., 2004).

The association between decreased crop yields and increased N_2O flux in no-till has been attributed partly to an asynchrony between crop N uptake rates and soil N availability (Six et al., 2004). Resulting changes in temporal patterns of soil inorganic N availability coupled with greater water-filled pore space and C availability stimulate N_2O production. In our system, no-till did not significantly affect crop yields averaged over the entire experiment, although in 1992 (soybean), 1996 (corn), and 1997 (soybean) there were higher yields in no-till, suggesting that this asynchrony did not differ between treatments.

Our results demonstrate that N_2O emissions are a major component of the GWP of agricultural ecosystems (Table 2). In both systems, N_2O contributed to the atmosphere around 55 g m^{-2} yr^{-1} of CO_2 equivalents, sufficient to offset 56 to 61% of the reduction in GWP associated with soil C sequestration in the top 5 cm. These results are consistent with Robertson et al. (2000) who found that 51% of the soil C storage to 7 cm in no-till was offset by N_2O emissions between 1991 and 1999 in these plots. Both of these C sequestration estimates, although consistent with other estimates from Midwest cropping systems, are based on C measurements taken near the soil surface. Other studies have shown lower subsurface C sequestration rates in no-till, or even reduced C storage, beneath the soil surface of no-till compared to conventional till (Davidson and Ackerman, 1993; West and Post, 2002). Total profile C storage thus needs to be determined to ascertain a more accurate estimate of total ecosystem GWP for these two tillage systems; nonetheless, the analysis we report here, and that of Robertson et al. (2000), highlight the magnitude and importance of N_2O emissions from fertilized agricultural systems. Over time, C sequestration rates will slow down in the no-till soils as they approach a new C equilibrium (West and Post, 2002) and, concomitantly, the proportion of annual C sequestration that is offset by N_2O emissions will increase.

Robertson et al. (2000) found that conventional till, no-till, low-input, organic, and continuous alfalfa cropping systems at the KBS LTER site produced statistically similar N_2O emissions between 1991 and 1999 and that only successional communities, where soil N concentrations were substantially lower, had lower N_2O emission rates. In our soils, increases in N_2O emissions from no-till, per se, are nil or only a small proportion of the total N_2O flux from agricultural soils receiving supplemental anthropogenic N (Table 2). Asynchrony between N availability and crop uptake in systems receiving supplemental N results in excess soil inorganic N and enhanced N_2O production (MacKenzie et al., 1998; Grant et al., 2004). Efforts to mitigate N_2O emissions from agricultural cropping systems should thus focus on improving N use efficiency in cropping systems (Mosier et al., 1998; Mosier, 2001; McSwiney and Robertson, 2005) rather than on tillage differences. Management practices designed to better synchronize plant uptake with N availability have been described in detail elsewhere (Mosier et al., 1998; Council for Agricultural Science and Technology, 2004) and include using plant and soil sampling to more precisely match fertilizer inputs with crop N requirements, split N fertilizer applications, and slow-release fertilizers.

Changes in Yields and Soil Properties

In the northern Corn Belt of the United States, cold soils, compaction, and decreased N availability can be particularly problematic in no-till soils, resulting in yield declines (Mehdi et al., 1999; Vetsch and Randall, 2004). We found at this northern Corn Belt site no yield cost for no-till corn, soybean, or wheat. In fact, yields were similar in each system for all 14 years but three, during which yields were higher in no-till, indicating that lower soil NO_3^- concentrations were not associated with yield losses.

The use of starter N fertilizer, side-dress N, and a 2- to 3-yr rotation in our experiment likely contributed to the persistence of equal or greater yields in no-till. These management strategies reduce intermittent N limitation from low mineralization rates or fertilizer N immobilization in no-till. Vetsch and Randall (2000) reported an increase in continuous corn yields of 0.5 Mg ha^{-1} when starter fertilizer was used in no-till systems and Vetsch and Randall (2002) concluded that optimizing no-till corn yields following soybean also required the use of starter fertilizer. Starter fertilizer enhances early season crop growth and increases corn yields in no-till soils that may be susceptible to spring N deficiencies (Jokela, 1992; Bullock et al., 1993). Side-dressing N after corn emergence further optimizes crop N use efficiency by targeting the crop when it is actively removing soil N (Fox et al., 1986; Mosier et al., 1998; Vetsch and Randall, 2004). In a review of N cycling in no-till, Martens (2001) suggested that N limitation may not be as great when corn is grown in rotation with other crops with differing N requirements.

Increased aggregation and soil C content indicates that, over time, no-till may have become a better habitat for crop growth. Increased aggregate MWD will improve aeration and drainage, and make the system more resilient to compaction. Increased soil C concentrations will improve soil structure and erosion resistance (Grandy et al., 2002), and potentially increase the N mineralization potential during the growing season when soils are sufficiently warm to support active decomposition.

Trends over Time

Predicting N_2O emissions and crop yields in no-till systems depends on understanding short-and long-term dynamics following transition to no-till. The potential for N cycling, crop yield, and N_2O emissions in no-till to be dependent on the time since conversion has been demonstrated by other studies (Rice et al., 1986; Vyn and Raimbault, 1993; Six et al., 2004). We did not detect a trend through time in the difference between till and no-till for soil water content, N_2O emissions, soil nitrate and ammonium, or crop yields. There was, however, some inter-annual variability; corn yields, for example, in both treatments were lower in 1996, 1999, and 2002 than in previous years due to localized, seasonal droughts during critical stages of corn development.

There was some evidence of changes in N cycling shortly after the adoption of no-till. Relatively high rates of N_2O flux were measured in 1991 and although these differences were not sustained, they do corroborate other results showing the potential for increased N_2O production after no-till conversion (Ball et al., 1999; Yamulki and Jarvis, 2002; Baggs et al., 2003). Additionally, there seemed to be a trend toward decreased soil N concentrations in no-till corn over time. In 1989, the NO_3^- concentrations were the same in both treatments, but in 1991, 1996, 1999, and 2001 there was lower NO_3^- in no-till sites. However, linear regression, even with the anomalous 1991 results removed (data not shown), did not show a significant relationship between time and normalized NO_3^- difference.

Long-term responses to no-till may vary considerably with soil type, climate, and management practices and their effects on litter accumulation and soil bulk density. Following conversion to no-till, increased N immobilization is likely where litter C accumulates rapidly at the soil surface (Baggs et al., 2003), and N_2O production should increase where increased bulk density alters soil pore-space dynamics (Linn and Doran, 1984; MacKenzie et al., 1998). McConkey et al. (2002) reported that N cycling and grain yield responses to no-till varied considerably with soil type. On a sandy loam soil, the apparent N balances (applied N minus N removed in grain) were 26% greater in no-till than in minimum-till sites over 13 years of continuous wheat; on a clay soil the apparent N balance was 78% greater in no-till than in continuous till sites, suggesting that there was greater immobilization or gaseous losses of N on fine-textured soils. Several studies reporting increased N_2O emissions following no-till conversion have also been conducted on fine-textured soils including clay and silty clay loam (MacKenzie et al., 1997, 1998); imperfectly drained clay loam (Ball et al., 1999); clay loam (Aulakh et al., 1984); and silt loam (Baggs et al., 2003). In contrast, Elmi et al. (2003) found that no-till did not have higher N_2O emissions than conventional till on a sandy loam soil in Quebec, Canada.

Over time, increases in soil aggregation and associated soil physical properties and increased yields might decrease N_2O production in fine-textured, no-till soils. Rapid increases in N_2O emissions following cultivation of long-term no-till soils provides evidence for the benefits of long-term no-till (Estavillo et al., 2002; Pinto et al., 2004; Grandy and Robertson, unpublished data, 2005). In our system with relatively low clay contents and low rates of litter accumulation due to modest productivity and high decomposition rates, the negative effects of no-till are nil or short-lived.

CONCLUSIONS

At the KBS LTER site no-till increased soil C in the top 5 cm from 0.69 to 1.00 kg C m^{-2} and increased aggregate MWD from 1.32 to 2.04 mm. Nitrous oxide emissions were higher in no-till in two of ten years but there was no significant effect of tillage averaged across years. Nitrous oxide emissions offset between 56 and 61% of the CO_2 reduction associated with C sequestration in no-till. In the three years where significant tillage effects on yield occurred, no-till had higher yields than conventional till, indicating that decreases in N availability with no-till did not reduce yields. There were no trends in soil N cycling, yields, or N_2O emissions across all years. Our results demonstrate that the adoption of no-till can increase soil C storage and physical structure without increased N_2O emissions or yield trade-offs.

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