Title

The potential to mitigate global warming with no-tillage management is only realized when practised in the long term

Journal

Global Change Biology, 10(2)

ISSN

1354-1013

Authors

Six, J
Ogle, S M
Breidt, F J
et al.

Publication Date

2004-02-01

Global Change Biology (2004) **10,** 155–160, doi: 10.1111/j.1529-8817.2003.00730.x

The potential to mitigate global warming with no-tillage management is only realized when practised in the long term

JOHAN SIX*†, STEPHEN M. OGLE†, F. JAY BREIDT‡, RICH T. CONANT†, ARVIN R. MOSIER§ and KEITH PAUSTIAN†

**Department of Agronomy and Range Science, University of California, Davis, CA 95616, USA, †Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA, ‡201 Statistics, Colorado State University, Fort Collins, CO 80523, USA, §USDA/ARS, 301 South Howes, Federal Building Room 420, Fort Collins, CO 80521, USA, ¶Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO 80523, USA*

Abstract

No-tillage (NT) management has been promoted as a practice capable of offsetting greenhouse gas (GHG) emissions because of its ability to sequester carbon in soils. However, true mitigation is only possible if the overall impact of NT adoption reduces the net global warming potential (GWP) determined by fluxes of the three major biogenic GHGs (i.e. CO_2, N_2O, and CH_4). We compiled all available data of soil-derived GHG emission comparisons between conventional tilled (CT) and NT systems for humid and dry temperate climates. Newly converted NT systems increase GWP relative to CT practices, in both humid and dry climate regimes, and longer-term adoption (>10 years) only significantly reduces GWP in humid climates. Mean cumulative GWP over a 20-year period is also reduced under continuous NT in dry areas, but with a high degree of uncertainty. Emissions of N_2O drive much of the trend in net GWP, suggesting improved nitrogen management is essential to realize the full benefit from carbon storage in the soil for purposes of global warming mitigation. Our results indicate a strong time dependency in the GHG mitigation potential of NT agriculture, demonstrating that GHG mitigation by adoption of NT is much more variable and complex than previously considered, and policy plans to reduce global warming through this land management practice need further scrutiny to ensure success.

Keywords: global warming potential, greenhouse gas mitigation, nitrous oxide, no-tillage

Received 20 August 2003; revised version received and accepted 9 October 2003

Introduction

It has been estimated on a global scale that the agricultural sector has the potential to reduce radiative forcing of greenhouse gases (GHGs) by 1.15–3.3 Pg C equivalents per year (Cole *et al*., 1997). No-tillage (NT) farming has been promoted as an agricultural practice that creates a 'win–win' situation by reducing soil erosion and enhancing agricultural sustainability concomitant with mitigating GHG emissions (Cole *et al*., 1997; Paustian *et al*., 1997; Schlesinger, 1999). The potential to offset GHG emissions from energy and industrial sources is largely based on studies documenting the CO_2 mitigation potential with NT (Kern & Johnson, 1993; West & Marland, 2002), and consequently some planned emissions trading between industry and producers is based on uptake of CO_2 from the atmosphere and subsequent soil storage of C following adoption of NT. However, this type of emission trading may fail to reduce potentially deleterious effects of GHG emissions on the climate if it does not consider the net result of fluxes for all three major biogenic GHGs (i.e. CO_2, N_2O, and CH_4) on radiative forcing, which is essential for understanding agriculture's impact on net global warming potential (GWP) (Kessavalou *et al*., 1998; Robertson *et al*., 2000; Oenema *et al*., 2001; Smith *et al*., 2001). Nevertheless, only few studies have considered the fluxes of all three major GHGs that are impacted by tillage management.

Correspondence: J. Six, Department of Agronomy and Range Science, University of California, Davis, CA 95616, USA, tel: +1 530 752 1212, fax: +1 530 752 4361, e-mail: jwsix@ucdavis.edu

Therefore, the objective of this study was to assess potential global warming mitigation with the adoption of NT in temperate regions by compiling all available data reporting differences in fluxes of soil-derived C, N_2O, and CH_4 between conventional tilled (CT) and NT systems. Through this analysis, we provide a broader assessment of the role of NT for GHG mitigation purposes than in previous published analyses that were based solely on carbon sequestration.

Materials and methods

Literature review

We selected studies evaluating direct comparisons between NT and CT in order to isolate the effect of tillage from other management change (e.g. increased cropping intensity) that may concomitantly occur with NT adoption. Also, studies were only included if there was constancy in edaphic and topographic characteristics between the NT and CT treatment. Conventional tillage completely inverts the soil (e.g. moldboard plowing), while NT creates a negligible amount of soil disturbance (a narrow slot is opened for seed insertion with NT planters). Our dataset included 254 data points for comparisons of soil C, 44 data points for nitrous oxide comparisons, and five data points for comparisons of CH_4 fluxes. Because the moisture regime has a pervasive influence on soil-derived GHG emissions, we divided the dataset into humid and dry climate subsets based on Holdridge Life Zones (Holdridge *et al.*, 1971), which classify areas with potential evaporation/mean annual precipitation ratio >1 as dry climates and areas with ratio <1 as humid climates. Location, climate regime, and associated GHG flux measurements of all sites are presented in Fig. 1. Sites in the US Corn Belt dominated comparisons for humid climates, whereas sites in the North American Great Plains dominated the dry climate comparisons.

Statistical analyses

Differences in soil organic carbon storage between NT and CT systems were analyzed in a linear mixed-effect model, with fixed effects for depth, climate (wet or dry) and years since the management change, and random effects accounting for dependencies in time series data and inclusion of multiple depth increments from a single experiment in the analysis (Ogle *et al.*, 2003).

Individual depth increments were not aggregated in this model. Instead, to accommodate data from different increment ranges, we treated the effect of depth on soil organic carbon as a quadratic function, which allows for the possibility that management impacts would be greatest at the surface and diminish with depth. Soil organic carbon measured on a particular depth increment ($U=$ upper endpoint of increment, in cm; $L=$ lower endpoint of increment, in cm) is assumed to be the integrated average of the quadratic function over the increment. Two regressors were formed from

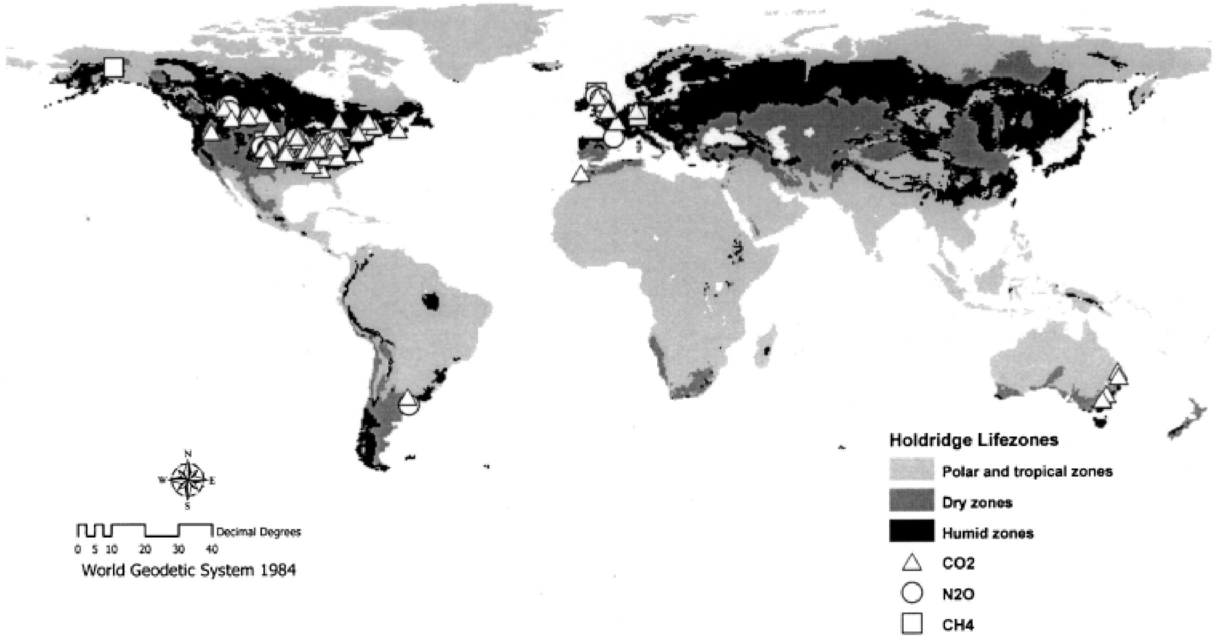

Fig. 1. Location of agricultural experiment sites included in our analysis.

the upper and lower values of each increment to account for the integration and averaging of the quadratic function across each depth increment:

$$x_1 = (L^2 - U^2)/(2 \times (L - U)) \text{ and } \quad x_2 = (L^3 - U^3)/(3 \times (L - U). \tag{1}$$

Changes in soil organic carbon storage are cumulative measures of the management effects on CO_2 fluxes. Therefore, the estimated change at 20 years from the linear mixed-effect model represented the cumulative difference in carbon storage between NT and CT systems, with corresponding uncertainty given by the estimated variance from the model for that prediction. To estimate the difference in soil organic carbon storage between NT and CT for a specific year (i.e. 5, 10, or 20 years), we used the following equation:

$$\Delta\text{SOC} = X_t/t, \tag{2}$$

where t is the year of interest, and X_t is the cumulative value, which was given by the linear mixed-effect model. The uncertainty in an estimate for a single year was assessed using the equation

$$\text{Var}(\Delta\text{SOC}) = 1/t^2 \times (\text{Var}\, X_t), \tag{3}$$

where $\text{Var}(X_t)$ is the estimated variance for the cumulative change in year t, which is given by the model.

Differences in nitrous oxide fluxes between CT and NT management were also analysed in a linear mixed-effect model. Within the model, years and climate were fixed effects and a random effect accounted for dependence in time series data and measurements from different crop rotations within a single study. We attempted to fit different random effects for these two sources of variation, but there were not enough data to separate the effects. In contrast to soil C data, nitrous oxide flux measurements represent the emission for the year in which the data were collected. Therefore estimated annual differences in emissions at years 5, 10, and 20 were provided directly from the model, with corresponding uncertainty given by variances of predictions. To obtain a cumulative estimate at t years (i.e. 20 years), we used the following equation

$$\Delta N_2O = X_1 + X_2 + \cdots + X_t, \tag{4}$$

where X_i represents the annual difference in nitrous oxide flux between CT and NT systems, and t is the total number of years of interest for the cumulative estimate. Uncertainty was estimated from the equation:

$$\text{Var}(Y) = x'Vx, \tag{5}$$

where x is the summed covariate vector for the regression coefficients of the linear mixed-effect model, and V is the estimated variance–covariance matrix for the coefficients.

Differences in methane fluxes between CT and NT systems had only been evaluated in four studies, and so we did not attempt to statistically model climate effects or year-to-year changes as we did with soil C and nitrous oxide data. Instead, we used the mean difference in methane fluxes to estimate the annual changes in years 5, 10, and 20, along with the estimated variance of the mean as a measure of uncertainty. To estimate the cumulative impact of management change over 20-year period, we used the equation

$$\Delta CH_4 = Xt, \tag{6}$$

where X is the mean annual flux and t is the number of years over which the cumulative estimation is made. The corresponding uncertainty was estimated from the equation

$$\text{Var}(\Delta CH_4) = t^2\text{Var}(X), \tag{7}$$

where $\text{Var}(X)$ is the variance from the mean annual flux. All statistical analyses were performed using S-PLUS 2000 (Professional Release 3; Insightful Corporation, Seattle WA, USA).

Global warming potential calculations

We used the IPCC factors (IPCC, 2001) to calculate GWP in CO_2-equivalents $ha^{-1}\,yr^{-1}$ over a 100-year time horizon for the estimated differences in soil organic carbon, nitrous oxide, and methane, using the following equations:

$$\Delta\text{GWP}(CO_2) = \Delta\text{SOC} \times 44/12 \times (-1), \tag{8}$$

$$\Delta\text{GWP}(N_2O) = \Delta N_2O \times 296, \tag{9}$$

$$\Delta\text{GWP}(CH_4) = \Delta CH_4 \times 23. \tag{10}$$

Then, we calculated total GHG balance or net GWP using the equation:

$$\Delta\text{GWP} = \Delta\text{GWP}(CO_2) + \Delta\text{GWP}(N_2O) + \Delta\text{GWP}(CH_4). \tag{11}$$

To combine uncertainties for the total GWP calculation, we converted the individual variances into CO_2 equivalents and summed those values using the equation

$$\text{Var}(\Delta\text{GWP}) = \text{Var}(\Delta\text{GWP}(CO_2)) + \text{Var}(\Delta\text{GWP}(N_2O)) + \text{Var}(\Delta\text{GWP}(CH_4)). \tag{12}$$

The square root of this sum is the estimated standard deviation. This computation of uncertainty implicitly assumes that the three components of total GWP are uncorrelated. One of the studies used in our dataset (Kessavalou *et al.*, 1998) had simultaneously examined the three components, and correlations among the fluxes were weak, suggesting that the estimated variance based on no correlation among the fluxes is a useful indicator of actual uncertainty. If there were in fact non-negligible correlations, the estimated variance could increase or decrease depending on the signs and magnitudes of correlations.

Results and discussion

In humid climates, net soil organic C storage within the 0–30 cm soil layer averaged 222 kg C ha^{-1} yr^{-1} over the first 20 years following adoption of NT practices (Table 1). In contrast, NT adoption in dry climates was estimated to result in C emissions at years 5 and 10, whereas the trend changed to net C sequestration during the second decade and averaged 97 kg C ha^{-1} yr^{-1} by year 20. These rates are low compared to the average sequestration rate of 480 kg C ha^{-1} yr^{-1} reported by West & Post (2002). However, they included tropical studies that tend to have higher sequestration rates than studies from temperate zones and did not consider the time dependence of these rates. Interestingly, West & Post (2002) did find a similar climatic trend as our analysis that showed NT adoption in rotations that have a bare fallow year, which are indicative of rotations in dry climates, had less or even no carbon sequestration relative to CT systems. Several studies have reported minimal C sequestration with NT adoption in the North American Great Plains Region when adoption is not coupled with cropping intensification (i.e. removal of fallow), especially when considering changes in soil organic C at soil layers deeper than 0–5 cm (Peterson *et al.*, 1998; Halvorson *et al.*, 2002). It is significant that adoption of NT in dry climates leads to an initial loss of C in the 0–30 cm soil layer for the first 5 years. This pattern has been observed in other short-term studies as well (Hendrix, 1997). This early trend may be due to a slower incorporation of surface residues into the soil through soil faunal activity than is found in corresponding CT systems where these residues are incorporated through plowing.

In both humid and dry climates, differences in N_2O-fluxes between the two tillage systems changed over time (Table 1). In the first 10 years, N_2O-fluxes were higher in NT than CT systems, regardless of climate. After 20 years, however, N_2O-fluxes in humid climates were lower in NT than CT systems and were similar between tillage systems in the dry climate. Increased N_2O-fluxes following adoption of NT is not necessarily

Table 1 Annual differences in soil-derived greenhouse gas fluxes and global warming potential (GWP) between no-till and conventional till systems

	No-till − conventional till											
	Year 5				Year 10				Year 20			
	(kg ha^{-1} yr^{-1})		GWP		(kg ha^{-1} yr^{-1})		GWP		(kg ha^{-1} yr^{-1})		GWP	
	Estimate	SE†	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Soil organic C												
Humid	194	4	−710	16	213	2	−780	7	222	1	−815	4
Dry	−306	6	1123	21	−37	3	137	10	97	2	−356	6
N_2O												
Humid	3.8	0.8	1114	237	1.1	0.8	330	222	−4.2	1.9	−1238	565
Dry	1.3	1.5	398	431	0.9	1.2	268	367	0.0	1.6	8	466
CH_4												
Humid	−0.6	0.1	−13	3.1	−0.6	0.1	−13	3.1	−0.6	0.1	−13	3.1
Dry	−0.6	0.1	−13	3.1	−0.6	0.1	−13	3.1	−0.6	0.1	−13	3.1
Soil-derived GWP												
Humid			391	238			−463	222			−2066	565
Dry			1508	432			392	367			−361	466

†SE = standard error and GWP units are CO_2 equivalents (kg ha^{-1} yr^{-1}). Values in the columns headed by year 5, 10 and 20 are estimates for 5, 10 and 20 yr after conversion from conventional till to no-till. Estimates are based on output of linear mixed-effect modelling of all currently available data. Negative numbers indicate a reduction in global warming potential or a mitigation of global warming.

surprising because of a transient yet significant N deficiency which lowers crop yields in recently established NT systems (Bandel *et al*., 1975; Blevins *et al*., 1977; Rice *et al*., 1986; Vetsch & Randall, 2000). This observed N deficiency has been associated with increased N_2O-emissions in NT systems (Burford *et al*., 1981; Rice & Smith, 1982; Linn & Doran, 1984). In addition, greater soil water content (Blevins *et al*., 1971; Cox *et al*., 1990) and percentage of water-filled pore space (Linn & Doran, 1984; Kessavalou *et al*., 1998) have been observed following NT adoption and are known to stimulate denitrification and resulting N_2O emissions (Linn & Doran, 1984). These changes in soil moisture and their impact on denitrification would account for the loss of nitrogen and subsequent mineral deficiency for crop production. The higher N_2O-fluxes during the first 10 years after conversion to NT from CT but decreased N_2O-fluxes thereafter are in accordance with the results of Keller *et al*. (1993). They reported threefold higher N_2O-fluxes in recently formed pastures than in the original forest, but after 10 years of conversion N_2O-fluxes were lower in the pasture than in the original forest.

The few studies reporting CH_4-flux differences between CT and NT systems all found a significant enhancement of CH_4 uptake (averaging 0.6 kg ha^{-1} yr^{-1}) with NT adoption (Table 1). Greater pore continuity and the presence of ecological niches for methanotrophic bacteria in NT systems lead to increased CH_4 uptake relative to CT systems (Hutsch, 1998).

Considering the three GHG fluxes together changes the temporal horizon over which soils under NT are likely to mitigate global warming. Since N_2O is such a potent GHG, greater N_2O fluxes offset the benefits resulting from C sequestration and CH_4 uptake, leading to increases in net GWP during the first 5 and 10 years following NT adoption in both humid and dry climates (Table 1). After 20 years of NT adoption, however, net GWP is strongly negative in humid climates. In dry climates, GWP is weakly negative, but the uncertainty prevents a definitive conclusion regarding its significance. The GWP estimates for both humid and dry climates have a large degree of uncertainty because N_2O-fluxes have a disproportionate impact on the calculations due to the potency of N_2O as a GHG, and due to the fact that the uncertainties associated with N_2O-fluxes are so large (Mosier *et al*., 1996).

To integrate impacts over time, we calculated the cumulative GHG fluxes and GWP over the 20-year time span of our data (Table 2). In humid climates, high C sequestration rates and relative decreases in N_2O-fluxes over time lead to a mean cumulative negative GWP for NT relative to CT. In drier areas, negative or low C sequestration rates were not enough to compensate for increases in N_2O-emissions, resulting in a zero-balanced mean cumulative GWP. However, it is worth noting that NT adoption in dry climates can be combined with an increase in cropping intensity, which typically increases C sequestration rates (Peterson *et al*., 1998; Franzluebbers & Steiner, 2002; Halvorson *et al*., 2002) and might therefore lead to a negative GWP. In addition, changes in agricultural inputs (fuel, fertilizer, etc.) under NT can lead to ancillary emission reductions of as much as 31 kg C ha^{-1} yr^{-1} or 2273 kg ha^{-1} CO_2-equivalents over 20 years (West & Marland, 2002), primarily due to lower fuel consumption (Table 2).

Table 2 Twenty years cumulative differences in soil-derived, ancillary and total greenhouse gas fluxes and global warming potential (GWP) between no-till and conventional till systems

	No-till − conventional till			
	(kg ha^{-1})		GWP	
Humid climate	Estimate	SE	Estimate	SE
Soil Organic C	4440	38	−16296	88
N_2O	17	13	5027	3706
CH_4	−11	2	−258	46
Soil-derived GWP			−11526	3707
Ancillary GHG changes	−31		−2273	
Total GWP			−13799	
Dry climate				
Soil organic C	1942	54	−7128	115
N_2O	17	20	5105	5814
CH_4	−11	2	−258	46
Soil-derived GWP			−2281	5815
Ancillary GHG changes	−31		−2273	
Total GWP			−4554	

SE = standard error and GWP units are CO_2 equivalents (kg ha^{-1} yr^{-1}). Soil-derived estimates are based on output of linear mixed-effect modelling of all currently available data. Ancillary greenhouse gas (GHG) changes are due to changes in agricultural input (e.g., fuel); adopted from West and Marland (2002). Negative numbers indicate a reduction in global warming potential or a mitigation of global warming.

Conclusion

It is highly significant that the overall effect of N_2O emissions on the net balance of GHG fluxes under NT fundamentally changes the GWPs over time and that the current uncertainty around estimates of this net balance is so large. Consequently, current promotion of NT agriculture to reduce GHG emissions and, therefore, radiative forcing needs additional consideration beyond just the benefit of carbon sequestration. Encouraging NT may indeed be a wise policy decision, but without sound scientific assessment and understanding of the overall short- and long-term net changes in radiative forcing with NT adoption under different management regimes, there is the potential for promoting unproductive and even deleterious changes in agricultural policies. It is, therefore, crucial to further investigate the long-term, as well as the immediate effects of various N-management strategies, such as precision farming, nitrification inhibitors, and type plus method of N fertilizer application, for purposes of long-term reduction of N_2O-fluxes under NT conditions. Increasing N fertilizer use efficiency concomitant with long-term reduced N_2O-losses would represent a very desirable and more definitive 'win–win' situation.

Acknowledgments

This work was supported by the National Science Foundation, US Department of Agriculture, US Environmental Protection Agency, and the Department of Energy. We thank K. A. Smith and W. M. Post for insightful comments on an earlier draft and A. Swan for help with the graphics.

References

Bandel VA, Dzienia S, Stanford G *et al.* (1975) N behavior under no-till vs. conventional corn culture. I. First-year results using unlabeled N fertilizer. *Agronomy Journal*, **67**, 782–786.

Blevins RL, Cook D, Phillips SH *et al.* (1971) Influence of no-tillage on soil moisture. *Agronomy Journal*, **63**, 593–596.

Blevins RL, Thomas GW, Cornelius PL (1977) Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. *Agronomy Journal*, **69**, 383–386.

Burford JR, Dowdell RJ, Crees R (1981) Emission of Nitrous oxide to the atmosphere from direct-drilled and ploughed clay soils. *Journal of the Science of Food and Agriculture*, **32**, 219–223.

Cole CV, Duxbury J, Freney J *et al.* (1997) Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutrient Cycling in Agroecosystems*, **49**, 221–228.

Cox WJ, Zobel RW, van Es HM (1990) Tillage effects on some soil physical and corn physiological characteristics. *Agronomy Journal*, **82**, 806–812.

Franzluebbers AJ, Steiner JL (2002) Climatic influences on soil organic carbon storage with no tillage. In: *Agricultural Practices and Policies for Carbon Sequestration in Soil* (eds Kimble JM, Lal R, Follett RF), pp. 71–85. Lewis, Boca Raton.

Halvorson AD, Wienhold BJ, Black AL (2002) Tillage, nitrogen, and cropping system effects on soil carbon sequestration. *Soil Science Society of America Journal*, **66**, 906–912.

Hendrix PF (1997) Long-term patterns of plant production and soil carbon dynamics in a Georgia Piedmont agroecosystem. In: *Soil Organic Matter in Temperate Agroecosystems. Long-Term Experiments in North America* (eds Paul EA, Paustian K, Elliott ET *et al.*), pp. 235–245. CRC Press, Boca Raton, FL.

Holdridge LR, Grenke WC, Hatheway WH *et al.* (1971) *Forest Environments in Tropical Life Zones*. Pergamon Press, Oxford.

Hutsch BW (1998) Tillage and land use effects on methane oxidation rates and their vertical profiles in soil. *Biology Fertility Soils*, **27**, 284–292.

IPCC (2001) Climate change 2001: the scientific basis. In: *Intergovernmental Panel on Climate Change* (eds Houghton JJ *et al.*) pp. 881 Cambridge University Press, Cambridge, UK.

Keller M, Veldkamp E, Weitz AM (1993) Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica. *Nature*, **365**, 244–246.

Kern JS, Johnson MG (1993) Conservation tillage impacts on national soil and atmospheric carbon levels. *Soil Science Society of America Journal*, **57**, 200–210.

Kessavalou A, Mosier AR, Doran JW (1998) Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. *Journal of Environmental Quality*, **27**, 1094–1104.

Linn DM, Doran JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. *Soil Science Society of America Journal*, **48**, 1267–1272.

Mosier AR, Duxbury JM, Freney JR *et al.* (1996) Nitrous oxide emissions from agricultural fields: assessment, measurement and mitigation. *Plant and Soil*, **181**, 95–108.

Oenema O, Velthof G, Kuikman P (2001) Technical and policy aspects of strategies to decrease greenhouse gas emissions from agriculture. *Nutrient Cycling in Agroecosystems*, **60**, 301–315.

Ogle SM, Eve MD, Breidt FJ *et al.* (2003) Management impacts on soil organic carbon storage in US agroecosystems: literature review and synthesis. *Global Change Biology*, in press.

Paustian K, Andren O, Janzen HH *et al.* (1997) Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management*, **13**, 230–244.

Peterson GA, Halvorson AD, Havlin JL *et al.* (1998) Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. *Soil and Tillage Research*, **47**, 207–218.

Rice CW, Smith MS (1982) Denitrification in no-till and plowed soils. *Soil Science Society of America Journal*, **46**, 1168–1173.

Rice CW, Smith MS, Blevins RL (1986) Soil nitrogen availability after long-term continuous no-tillage and conventional tillage corn production. *Soil Science Society of America Journal*, **50**, 1206–1210.

Robertson GP, Paul EA, Harwood RR (2000) greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science*, **289**, 1922–1924.

Schlesinger WH (1999) Carbon sequestration in soils. *Science*, **284**, 2095.

Smith P, Goulding KW, Smith KA (2001) Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential. *Nutrient Cycling in Agroecosystems*, **60**, 237–252.

Vetsch JA, Randall GW (2000) Enhancing no-tillage systems for corn with starter fertilizers, row cleaners, and nitrogen placement methods. *Agronomy Journal*, **92**, 309–315.

West TO, Marland G (2002) A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. *Agriculture, Ecosystems and Environment*, **91**, 217–232.

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of America Journal*, **66**, 1930–1946.