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Managing soil organic carbon in agriculture: the net effect on greenhouse gas emissions

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ABSTRACT

A change in agricultural practice can increase carbon sequestration in agricultural soils. To know the net effect on greenhouse gas emissions to the atmosphere, however, we consider associated changes in CO_2 emissions resulting from the consumption of fossil fuels, emissions of other greenhouse gases and effects on land productivity and crop yield. We also consider how these factors will evolve over time. A change from conventional tillage to no-till agriculture, based on data for average practice in the U.S., will result in net carbon sequestration in the soil that averages 337 kg C ha^{-1} yr^{-1} for the initial 20 yr with a decline to near zero in the following 20 yr, and continuing savings in CO_2 emissions because of reduced use of fossil fuels. The long-term results, considering all factors, can generally be expected to show decreased net greenhouse gas emissions. The quantitative details, however, depend on the site-specific impact of the conversion from conventional to no-till agriculture on agricultural yield and N_2O emissions from nitrogen fertilizer.

1. Introduction

Increasing the carbon stocks of terrestrial ecosystems could mitigate global climate change by compensating for some of the CO_2 released to the atmosphere from fossil-fuel burning and other sources (see e.g. Kauppi et al., 2001). In keeping with this principle, the Framework Convention on Climate Change (UNFCCC, 1992) and the evolving Kyoto Protocol (UNFCCC, 1997) would allow, within a structured set of rules, countries to meet some of their commitments to reduce greenhouse gas emissions to the atmosphere by sequestering carbon in the biosphere. One of the options approved, with restrictions, in the Kyoto negotiations is to increase the content of soil organic carbon in agricultural soils. In addition to mitigating greenhouse gas emissions, carbon sequestration strategies for agricultural soils can provide environmental benefits such as decreased soil erosion, increased soil water capacity, increased retention of soil nutrients and increased productivity (Follett, 2001; Lal et al., 1999).

However, when assessing the potential for carbon sequestration in agricultural soils it seems appropriate to think beyond the amount of carbon physically sequestered in the soil (Schlesinger, 2000). Increasing the carbon stocks of agricultural soils involves changes in agricultural practices, and these changes may lead to additional impacts on greenhouse gas emissions that ought to be considered. Changing agricultural practices may involve changes in the use of fuel for machinery, agricultural inputs like fertilizers and pesticides, the productivity of agricultural lands and the emission of other greenhouse gases. Schlamadinger and Marland (1996) developed the Graz/Oak Ridge Carbon Accounting Model (GORCAM) to evaluate the net flux of greenhouse gases to the atmosphere for various forest management alternatives, and we have expanded this model to examine changes in greenhouse gas emissions as a result of changes in the management of agricultural lands.

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In this study we focus on the consequences that a change from conventional tillage to no-till agriculture might have on the emissions of greenhouse gases. Conversion to no-till is one of the more attractive agricultural options for increasing soil organic carbon (Follett, 2001; Lal et al., 1999). Our goal is to examine the full system of agricultural production to estimate the net change in greenhouse gas emissions if management practices are changed in order to increase soil carbon stocks. Inputs for crop production (e.g., fuel, fertilizer, pesticides, etc.) are based on U.S. agricultural statistics, circa 1995, and we use coefficients derived by West and Marland (2002a) to estimate the fossil-fuel use and CO_2 emissions associated with the production and use of these inputs.

We use the term "net C flux" to refer to the sum of carbon emissions and carbon sequestration for a given management system (West and Marland, 2002b). "Relative net C flux" refers to the difference between two systems. "Net C-equivalent (C_{eq}) flux" is used when we sum over multiple greenhouse gases according to their global warming potential; that is, according to their impact on the Earth's radiative balance when integrated over 100 yr (Houghton et al., 1996). Carbon fluxes are described relative to the atmosphere, i.e. carbon sequestration in soil is represented as negative values.

2. Model development and methods

The GORCAM model was developed as an accounting tool to estimate the net change in carbon flux to the atmosphere under alternate forest management strategies (Schlamadinger et al., 1998; Schlamadinger and Marland, 1996). Four primary components of net carbon flux to the atmosphere received primary consideration: storage of carbon in the biosphere, storage of carbon in forest products, use of biofuels to displace fossil fuels and use of wood products to displace other products that often require more fossil fuel for their production and use. Analyses showed that the initial condition, the growth rate of forests, the efficiency of product production and use and the time scale of the perspective were important parameters.

Agricultural ecosystems differ from forest ecosystems in that below-ground carbon stocks dominate above-ground carbon stocks, there are no long-lifetime products to consider, the energy and CO_2 implications of annual inputs to production play a larger role, product substitution takes a very different role, and the associated contribution of greenhouse gases other than CO_2 is more important. We have expanded GORCAM to examine these aspects of agricultural systems. GORCAM is an Excel® spreadsheet model that simulates and records carbon stocks and flows, and can be used in conjunction with @Risk® software to perform Monte Carlo analyses.

2.1. *Carbon dynamics in agricultural systems*

Carbon dioxide emissions from agricultural systems occur from: (a) plant respiration; (b) the oxidation of organic carbon in soils and crop residues; (c) the use of fossil fuels in agricultural machinery such as tractors, harvesters and irrigation equipment; and (d) the use of fossil fuels in the production of agricultural inputs such as fertilizers and pesticides. Carbon uptake occurs through photosynthesis. Carbon sequestration is represented by an increase in the stocks of carbon in any reservoir other than the atmosphere. Accumulation of organic carbon in soil can occur following changes in management that either increase the production of residue remaining on the field or decrease the loss of organic carbon in the form of carbon dioxide.

Management options for sequestering soil organic carbon (SOC) include a decrease in tillage intensity, a change from continuous to rotation cropping, and a decrease in fallow period (Paustian et al., 2000). We focus here on a change from conventional tillage (CT) to no-till (NT) agriculture. Conventional tillage is defined as management that leaves no more than 15% of the ground surface covered with crop residue after the subsequent planting has occurred. No-till management represents practice that leaves the ground undisturbed from harvesting to planting, while leaving 30% or more of the ground covered with surface residue after the subsequent planting (CTIC, 1998).

Following a change in agricultural management practices, soil organic carbon will gradually approach a new steady state that depends on the new suite of practices. West and Marland (2002a) have summarized a variety of experiments to derive typical values for the total amount by which soil carbon might be increased following a change from CT to NT, and the annual rate at which this increase typically occurs. Based on West and Marland (2002a), we approximate sequestration with a constant average rate for 20 yr following a change in practice and then with a steadily declining rate for another 20 yr (see also Lal et el., 1998 and Johnson et al., 1995). We assume that a new steady state is reached in 40 yr and no further increase in soil carbon will occur. We estimate emissions of CO_2 from agricultural machinery as the CO_2 emitted during use of the farm machinery and from the manufacture and repair of the machinery, averaged over the expected lifetime of the machinery. Emissions of CO_2 from agricultural inputs include those from production, packaging, and transport of materials such as fertilizers and pesticides.

A change in management practice can potentially affect agricultural yields or land productivity. If a new agricultural practice is adopted over a large area, a change in yield over this area could influence the crop supply and thus the crop price, which in turn could result in a change in the amount of land used to cultivate the specific crop. If, for example, crop yield decreased, then an additional amount of land might be brought into production to replace the loss in total yield. This increase in cropped area need not be in the same geographic place but would supply product to the same market. Altering land use to make up for any gain or loss in yield is represented in our computations with a land-use factor ranging from 0.0 to 1.0. Historic data from the U.S. National Agricultural Statistics Service (see West and Marland, 2002c) suggest that this land-use factor may have been closer to 0.2 over the last 40 yr for continuous corn crops within the U.S., indicating that for every 1% increase in yield, 0.2% of the cropped land was freed for other purposes or other crops. An estimate of the exact relationship between yield and land use would require the use of socio-economic models and is not attempted here. We make the initial assumption that if agricultural productivity changes, the area in production will change sufficiently to maintain constant agricultural output. We treat this factor as being symmetric for increases or decreases in yield.

When land is added to or released from crop production there will be changes in greenhouse gas emissions and soil carbon stocks on that land. In our analysis, if productivity increases and cultivated land is abandoned and allowed to revert to grassland or forest, an accumulation of 335 kg C ha^{-1} yr^{-1} is expected in the soil (Post and Kwon, 2000) and emissions from agricultural machinery and inputs on that land cease. This rate of carbon accumulation occurs for 20 yr and is followed by 20 yr of declining sequestration rates. For our model simulations, we use a sigmoidal relationship to describe the 40-yr period of soil carbon accumulation. If productivity decreases and grassland or forest is cleared and cultivated for agricultural production, there will be an estimated, average loss of 8000 kg C ha^{-1} of soil organic carbon over a 20-yr period (Mann, 1986), with the majority of carbon loss occurring in the first 5 yr (Davidson and Ackerman, 1993). We represent this declining carbon stock as an exponential decay. In this analysis we examine soil carbon and do not consider any carbon loss or sequestration from above-ground vegetation. The results could be considerably different if forests were cleared or created as agricultural productivity changed and if we included carbon in the above-ground vegetation in our analyses.

2.2. *Nitrogen dynamics in agricultural systems*

Nitrogen dynamics in agricultural systems are very much influenced by the large quantities added as nitrogen fertilizers. Anthropogenic emissions of the greenhouse gas nitrous oxide (N_2O) are often estimated directly from the amount of nitrogen applied as fertilizer (Houghton et al., 1997). In fact, emissions of N_2O from the application of N fertilizer are widely variable and depend on many soil chemical and physical properties. Emissions of N_2O also depend on the form and manner in which the nitrogen additions occur. The variability of N_2O flux over space and time has made it difficult to correlate emissions of N_2O with environmental variables or general ecosystem types (Groffman et al., 2000). An analysis by Bouwman (1994) suggested that, on average, $1.25 \pm 1.0\%$ of applied nitrogen was lost directly as N_2O, and this estimate was subsequently adopted by the Intergovernmental Panel on Climate Change (IPCC) in its workbooks for estimating anthropogenic greenhouse gas emissions (Houghton et al., 1997). In reviewing Bouwman's (1994) analysis, Mosier et al. (1996) estimated that an additional 0.75% of applied nitrogen was lost as N_2O indirectly (i.e. by leaching and volatilization). With some trepidation, and with an awareness of the variability that exists, our analysis assumes for a baseline that $2.0 \pm 1.0\%$ of applied nitrogen is lost to the atmosphere as N_2O (Mosier et al., 1998). Using a global warming potential of 310 (Houghton et al., 1996), this means that each kg of applied nitrogen results in the emission of 2.66 ± 1.33 kg C_{eq} as N_2O. This provides a first-order indication of the importance of N_2O emissions in the greenhouse gas balances.

Although there are not enough data available to do meaningful statistical analyses, emissions of N_2O from the soil (for similar nitrogen fertilizer application rates) may be different for CT and NT systems. The annual N_2O flux from continuous corn and corn rotations on heavy clay and silty clay loam soils in Quebec, Canada averaged about 38% greater from NT than from CT, for similar rates of N application (MacKenzie et al., 1997). Lemke et al. (1998) concluded that N_2O emissions from wheat systems in Alberta, Canada under NT were equal or less than that under CT. In an effort to better understand the spatial variability in agricultural N_2O emissions, as affected by tillage, Mummey et al. (1998) completed an analysis for the U.S. using the NGAS model, land-use data from the U.S. Department of Agriculture – Natural Resource Inventory data base, and weather data from the U.S. National Aeronautics and Space Administration. They concluded that NT in relatively warm and wet regions can result in similar or lower N_2O emissions than CT and, while NT in drier regions can result in greater N_2O emissions than CT. A weighted average of N_2O emission rates, using estimates from Mummey et al. (1998), suggested a 7% increase in N_2O emissions for NT, relative to CT, when the rate of nitrogen fertilizer application was the same. We recognize that N_2O emissions can vary greatly among sites and among management practices, and that detailed analyses will require site-specific numbers.

The rate of nitrogen fertilizer application also affects crop yield. Although a quadratic regression equation is often used to represent the effect of nitrogen on crop yield, a quadratic equation with an established maximum (referred to as a quadratic plus plateau) more accurately represents yield–response curves (Cerrato and Blackmer, 1990). Separate yield–response curves are used for CT and NT systems (Fox and Piekielek, 1987; Zhang and Blevins, 1996). Increased use of nitrogen fertilizer can also cause a decline in soil pH, which contributes to increased solubility of aluminium and magnesium and decreased availability of phosphorus, resulting in decreased yields. The decline in soil pH is commonly offset with the use of agricultural lime. In this analysis the application rate of lime varies linearly with nitrogen fertilizer, based on a relationship provided by Thomas and Frye (1984). With full introduction of nitrogen fertilizer as a variable in our model, nitrogen affects the net greenhouse gas balance in four ways: (a) CO_2 is released from the energy and fossil-fuel intensive production of nitrogen fertilizer, (b) crop yield changes as a function of nitrogen application rate, (c) the application rate and CO_2 emissions associated with the energy-intensive production of agricultural lime depend on the rate of nitrogen fertilization, and (d) N_2O emissions vary with tillage practice and as a function of nitrogen application rate.

3. Results

In general, carbon will be sequestered in the soil following a change from CT to NT agriculture. As noted above, conversion from CT to NT involves a variety of changes in practice that have implications for greenhouse gas emissions. Figure 1 summarizes the average change in greenhouse gas emissions in the years immediately following conversion from CT to NT, based on mean values for all crops in the U.S., circa 1995. Changes include increasing soil carbon stocks, decreased use of fossil fuels in machinery (because of fewer passes by agricultural equipment), increased use of nitrogen fertilizer and other agricultural inputs and the increased emissions of N_2O that accompany increased nitrogen fertilizer use. The numbers in Fig. 1 assume that changing from CT to NT does not result in any change in productivity.

The average sequestration rate of 337 kg C ha^{-1} yr^{-1} (to a depth of 30 cm) shown in Fig. 1 is based on a review (see West and Marland, 2002a) of 76 long-term experiments that monitored the effects of tillage practice on soil organic carbon. This rate of sequestration can be maintained for a limited number of years,

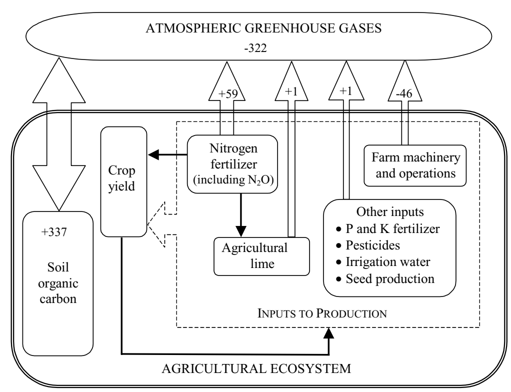

Fig. 1. Diagram of the agricultural component in GORCAM. Solid arrows indicate dynamic links in the model (e.g., the rate of N fertilizer affects crop yield, which influences the amount of cultivated land used to produce the crop that in turn alters inputs to production). Values embedded in arrows represent changes in flows of greenhouse gases following conversion from conventional tillage (CT) to no-till agriculture (NT), based on data for the average of all crops in the U.S., circa 1995. Emissions shown from nitrogen fertilizer include changes in N_2O emissions from fertilizer application and CO_2 emissions from production and transportation of the fertilizer. Units are kg C_{eq} ha^{-1} yr^{-1} and represent the average over the first 20 yr following conversion from CT to NT. Adapted from West and Marland (2002b).

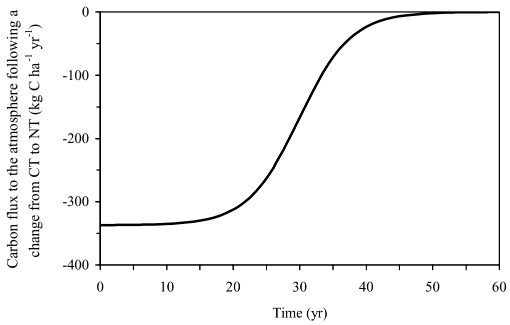

Fig. 2. Estimated soil carbon sequestration for the average U.S. crop, following a change from conventional tillage (CT) to no-till (NT), expressed in terms of net carbon flux to the atmosphere. Negative values show that the flow of carbon is negative with respect to the atmosphere, i.e. carbon is being sequestered in the soil. Values are based on a literature review summarized in West and Marland (2002a). While our model simulates sequestration with a steady, average rate of soil carbon sequestration during the initial 20 yr, it is likely that rates of soil carbon sequestration may be relatively lower during the initial 3–5 yr and peak between years 5 and 10 (Franzluebbers and Arshad, 1996).

and hence the literature review included the time path of sequestration. Based on our review of experimental data for all crops in the U.S., Fig. 2 shows a model of the average path of annual carbon sequestration as a function of time following the CT–NT conversion. While our simple model has adopted a steady, average soil carbon sequestration rate during the initial 20 yr, the data show wide year-to-year variability and suggest that rates of soil carbon sequestration are often relatively low during the initial 3–5 yr and peak between years 5 and 10 (see also Franzluebbers and Arshad, 1996). Numbers for carbon fluxes are with reference to the atmosphere, so negative values indicate carbon sequestration.

While the rates of carbon sequestration generally decline with time after a decade or two, the savings in fuel use and the increase in fertilizer use will continue as long as the NT system is maintained. Figure 3a shows the net C flux to the atmosphere over time when we sum the carbon sequestered and the change in carbon emissions from agricultural inputs. Figure 3 assumes that agricultural productivity is unchanged by the CT–NT transition and does not consider the contributions of other greenhouse gases. It is the carbon balance alone. In Fig. 3 savings in net carbon emissions extend beyond year 40 because reduced emissions from fossil-fuel use continue even though sequestration has ceased. This is particularly evident in

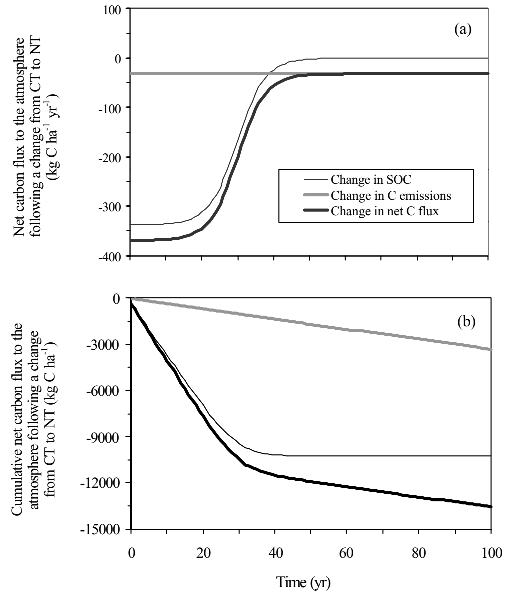

Fig. 3. Annual (a) and cumulative (b) changes in carbon emissions, soil organic carbon, and net carbon flux to the atmosphere following a change from CT to NT. The figure shows the difference between CT and NT and is based on U.S. average values for all crops, circa 1995. Based on data from West and Marland (2002a).

Fig. 3b, which shows the cumulative savings in carbon emissions to the atmosphere over time.

When changing from CT to NT there is a possibility that agricultural yields will also change. This possibility exists with any change in management and is not restricted to a change in tillage intensity. To consider the importance of this possibility, we have estimated net C flux to the atmosphere following a change from CT to NT and evaluated the sensitivity to a small change ($\pm$10%) in yield (Fig. 4). Figure 4a shows the annual change in net C flux to the atmosphere and Fig. 4b shows the cumulative savings in greenhouse gas emissions over 100 yr. In Fig. 4 carbon emissions are calculated per hectare, with reference to the number of hectares cultivated in the baseline CT system. The effect of decreased or increased yield is most apparent in the early years (Fig. 4a), when decreased yields lead to a less negative net carbon flux to the atmosphere (as carbon is released from newly cropped soils) and increased yields lead to a slightly more negative net carbon flux (as carbon accumulates in abandoned fields and inputs to production cease on these fields). The effect of changes in yield continues to accumulate over time, as the systems with higher yield require less input

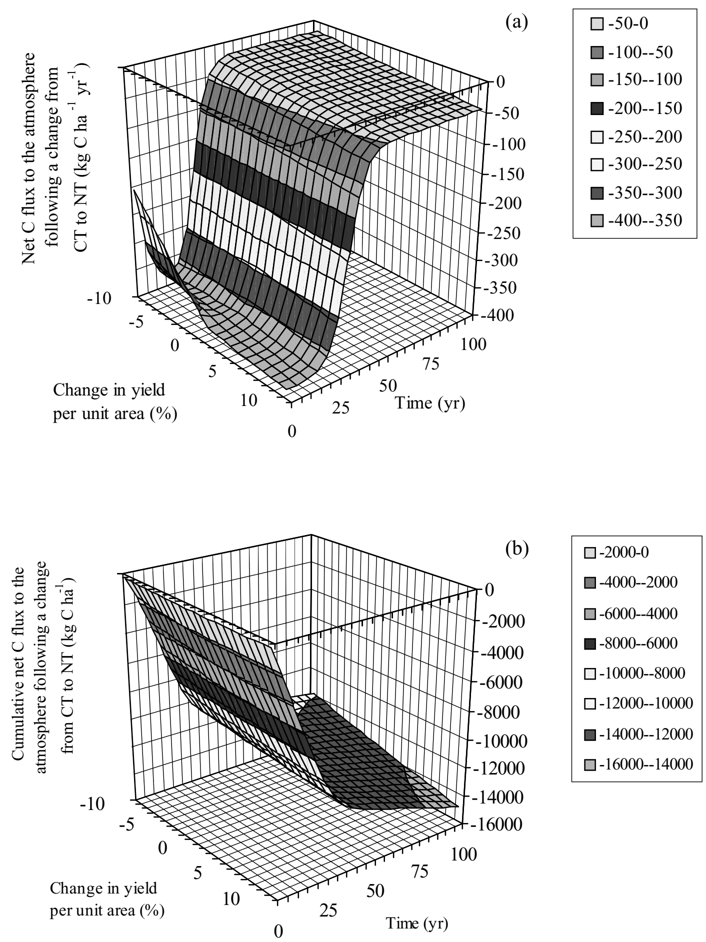

Fig. 4. Conversion from CT to NT, for the average U.S. crop, results in carbon sequestration in soil and a net decrease in fossil fuel use. It also has the potential to change agricultural productivity, and this figure shows the sensitivity to a $\pm 10\%$ change in crop yield. Here we assume that total agricultural output does not change because the area in production is adjusted to compensate for a change in yield per unit area. The figure shows the annual (a) and cumulative (b) net difference in carbon flux to the atmosphere following a change from CT to NT, as a function of change in yield per unit area. Values are shown per hectare, based on the number of hectares in the baseline CT system.

because less land is being cropped. Over a 100-yr period, a $\pm 10\%$ change in yield can result in a ± 1500 kg C ha^{-1} difference in net C flux to the atmosphere (Fig. 4b). Accumulation or loss of carbon in aboveground forest biomass, occurring due to the cultivation or abandonment of agricultural lands, was not considered in this analysis.

Finally, we enquire into the potential importance of considering other greenhouse gases. In particular, N_2O is a powerful and long-lived greenhouse gas and any changes in N_2O emissions could figure importantly in the balance of greenhouse gas emissions from agricultural systems. Recognizing that the assumption of a constant relationship between nitrogen fertilizer application and N_2O emissions is an inadequate representation in detail, we consider that there is likely to be a change in the rate of N_2O emissions following conversion from CT to NT and examine the sensitivity of the net greenhouse gas balance to a $\pm 20\%$ change in the rate of N_2O emissions per unit of fertilizer nitrogen applied as one moves from CT to NT. Figure 5 shows how the net effect on greenhouse gas

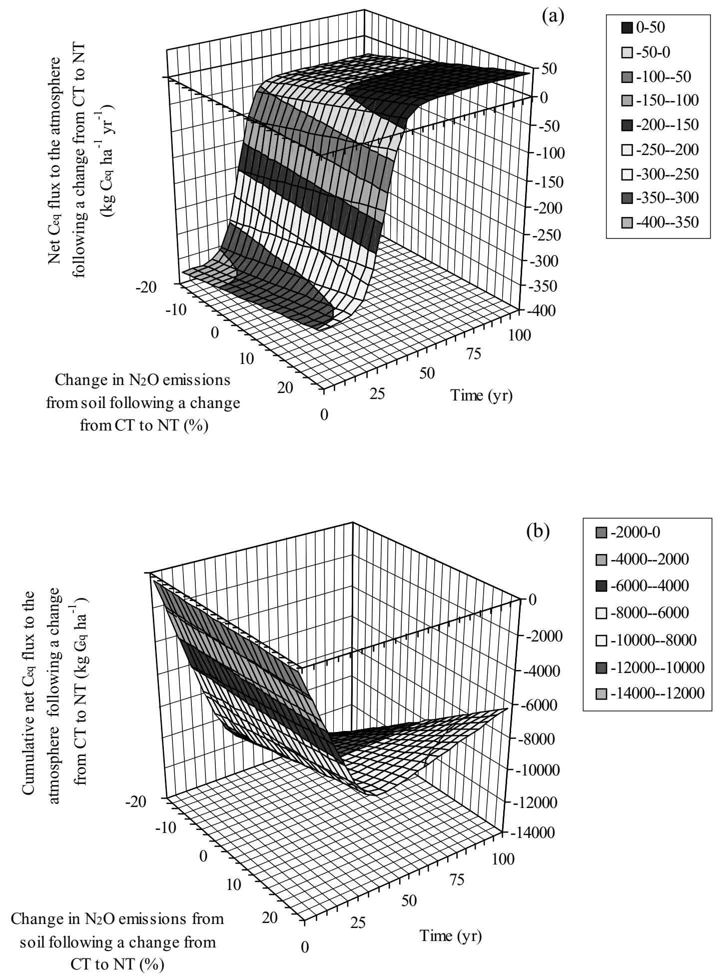

Fig. 5. Conversion from CT to NT, for the average U.S. crop, results in carbon sequestration in soil and a net decrease in fossil-fuel use. It can also result in a change in emissions of N_2O. We assume that N_2O emissions are 2.0% of the nitrogen applied as fertilizer (Mosier et al., 1998) and examine the sensitivity in carbon-equivalent emissions if this value changes by $\pm$20% as a result of the change from CT to NT. We use U.S. average values for carbon sequestration and inputs to agriculture and assume that crop yield is not changed. The figure shows the annual (a) and cumulative (b) change in emissions following a change from CT to NT, as a function of the ratio of N_2O emissions per unit of N fertilizer.

emissions, following conversion from CT to NT, is sensitive to a $\pm$20% change in the rate of N_2O emissions. Our assumption is that the emissions factor is constant within CT or NT systems but changes when the system changes. Figure 5 includes full consideration of carbon sequestration plus changes in fossil-fuel use, and assumes no change in agricultural productivity. Figure 5a shows the annual impacts on greenhouse emissions for 100 yr and Fig. 5b shows the cumulative effects.

To estimate the overall change in net C_{eq} flux to the atmosphere that would accompany a conversion from CT to NT, we have run a simulation for the average U.S. crop that included (a) the mean soil carbon sequestration rate of Fig. 2, i.e. 337 $\pm$ 108 kg C ha^{-1} yr^{-1} during the early years following conversion, (b) average U.S. production inputs and associated emissions for both CT and NT, (c) an estimated relationship between nitrogen fertilizer and N_2O emissions of 2.66 kg C_{eq} per kg N applied, (d) a potential change

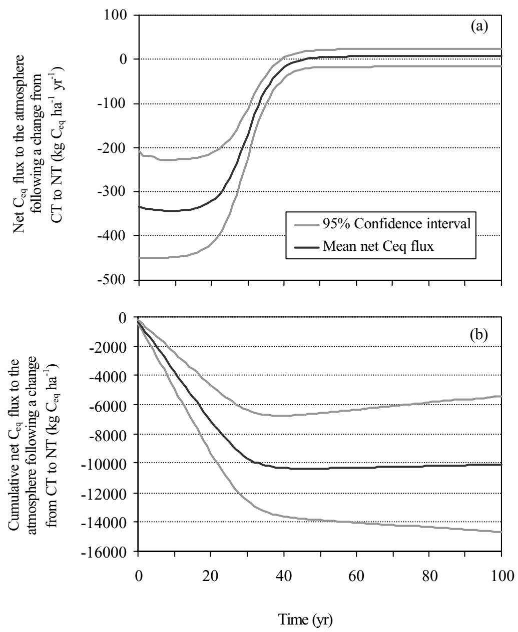

Fig. 6. The net effect on greenhouse gas emissions following conversion from CT to NT for the average of U.S. crops. A mean value and 95% confidence interval have been estimated with a Monte Carlo simulation over the range of values described in the text for the principal parameters. The annual (a) and cumulative (b) change in total greenhouse gas emissions are shown over 100 yr.

in N_2O emissions of 7 ± 15%, (e) a potential change in yield of ±6% and (f) a change in cropped area that ranged from full compensation for the change in crop yield to no response to the change in yield. We have used our best estimate of the mean and distribution of values for each variable and simulated the greenhouse gas balance over 100 yr using Monte Carlo risk analysis. For carbon sequestration we assumed normal distribution around 337 kg C ha^{-1} yr^{-1}. For estimated changes in N_2O emissions and in yield and land use, we assumed uniform distribution functions. Figure 6 shows the mean path of carbon sequestration bounded by the 95% confidence interval. Figure 6 suggests that for the average of U.S. crops, while accounting for all variability that may occur with a decrease in tillage, a change from CT to NT can reduce the net C_{eq} flux to the atmosphere by about 340 kg C_{eq} ha^{-1} yr^{-1} for the first 20 yr and by smaller amounts for another 20 yr. This translates into an estimated 10 000 ± 4000 kg C_{eq} ha^{-1} reduction in greenhouse gas emissions over a 40-yr period. After 40 yr, carbon sequestration will have ceased and the system will continue with minor gains or losses in net greenhouse gas emissions (with respect to the baseline CT system) depending on the balance between savings in fossil-fuel use and losses through N_2O emissions.

4. Conclusions

This analysis supports the contention that a change from conventional to no-till agriculture can be expected, on average, to result in increased carbon sequestration in agricultural soils. It further emphasizes that if our interest is in reducing net emissions of greenhouse gases to the atmosphere, careful consideration needs to be given to site-specific details that affect agricultural inputs, agricultural productivity and the evolution of N_2O from agricultural soils.

A change from CT to NT can change fuel use, crop yield and N_2O emissions. Our analysis of these factors is based on U.S. averages, and the carbon dynamics at any specific location will differ from average U.S. practice. The combined effect of these variables can significantly impact the net reduction in greenhouse gas emissions ascribed to carbon sequestration alone. This is especially true in the long term, when rates of soil carbon sequestration slow and approach zero but the management characteristics continue. Our sensitivity analyses suggest that there will generally be a net greenhouse gas reduction following a CT to NT conversion even if yields decrease somewhat and N_2O emissions increase, but the net gain will be very much eroded and of shorter duration. On the other hand, opportunities to improve fuel efficiency, crop productivity or the nitrogen balance can make important and, in some cases, long-term contributions to reducing net greenhouse gas emissions through carbon sequestration projects.

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