The conversion of the corn/soybean ecosystem to no-till agriculture may result in a carbon sink

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Abstract
Mitigating or slowing an increase in atmospheric carbon dioxide concentration ([CO₂]) has been the focus of international efforts, most apparent with the development of the Kyoto Protocol. Sequestration of carbon (C) in agricultural soils is being advocated as a method to assist in meeting the demands of an international C credit system. The conversion of conventionally tilled agricultural lands to no till is widely accepted as having a large-scale sequestration potential. In this study, C flux measurements over a no-till corn/soybean agricultural ecosystem over 6 years were coupled with estimates of C release associated with agricultural practices to assess the net biome productivity (NBP) of this no-till ecosystem. Estimates of NBP were also calculated for the conventionally tilled corn/soybean ecosystem assuming net ecosystem exchange is C neutral. These measurements were scaled to the US as a whole to determine the sequestration potential of corn/soybean ecosystems, under current practices where 10% of agricultural land devoted to this ecosystem is no-tilled and under a hypothetical scenario where 100% of the land is not tilled. The estimates of this analysis show that current corn/soybean agriculture in the US releases ~7.2 Tg C annually, with no-till sequestering ~2.2 Tg and conventional-till releasing ~9.4 Tg. The complete conversion of land area to no till might result in 21.7 Tg C sequestered annually, representing a net C flux difference of ~29 Tg C. These results demonstrate that large-scale conversion to no-till practices, at least for the corn/soybean ecosystem, could potentially offset ca. 2% of annual US carbon emissions.

Keywords: carbon sequestration; eddy covariance; global change; tillage practices

Introduction
A large proportion of all anthropogenically driven atmospheric carbon dioxide (CO₂) emissions since 1850 is attributable to land-use changes (Lal, 2004a). A major component of land-use change in the US was the conversion of presettlement prairie of the Midwestern US to agriculture, which currently and mostly consists of maize (Zea m. L.) and soybean (Glycine m. L. Merr.). Arguably, maize and soybean comprise the largest single ecosystem type in temperate North America. The model simulations suggest that the carbon (C) pool in the land in which this ecosystem is situated has decreased to 40% of the original because it was converted from presettlement prairie (Donigian et al., 1994; Lal, 2004a).

The possibility of sequestering C in agricultural soils has renewed research to convert from conventional-till agricultural practices to no-till farming (Lal & Kimble, 1997; Paustian et al., 1997; Potter et al., 1997; West & Post, 2002). Predicted increases in soil C sequestration associated with a switch from conventional-till practices to no-till practices is mostly linked with periodic measurements or models of soil organic carbon (SOC) (West & Post, 2002; West & Marland, 2002a, 2003; Del Galdo et al., 2003; Freibauer et al., 2004; Lal, 2004b; Smith, 2004). Results from these, and other, studies have cemented the notion that the potential for increased C sequestration in agricultural soils exists with changes in management practices. Direct measurements of soil C content, however, are confounded by interannual variability in rates of decomposition (Schlesinger, 1977), heterogeneity in root distribution, complications in the vertical distribution of SOC in the soil column (Jobbagy & Jackson, 2000), and the precision with which SOC can...
be measured (Wander et al., 1998; West & Marland, 2003).

The potential for Midwestern no-till agricultural systems to sequester C depends on the ability of vegetation to assimilate C from the atmosphere via photosynthesis and for that C to remain in the soil. To fully assess whether any agriculture system can be a net C sink, an analysis of the C costs associated with agricultural practices must be considered (West & Marland, 2002b, 2003; Marland et al., 2003; Lal, 2004a). The eddy covariance (EC) method provides an excellent opportunity to measure net ecosystem exchange (NEE) over agricultural systems to determine whether C sequestration potential exists. If NEE into the agricultural ecosystem, as measured by EC, is greater than the amount of C released from the system in the form of agricultural practices and grain consumption, then the potential for C sequestration exists. This accounting of all possible C sources and sinks for the corn/soybean ecosystem provides an estimate of the Net Biome Productivity (NBP) of the ecosystem (Schulze et al., 1999).

The objectives of this study were to determine (1) whether estimates of NBP reveal a potential to sequester C into a no-till maize/soybean rotation agricultural ecosystem and (2) to quantify the amount of C that is currently sequestered in the US and the amount that might be sequestered in the US if no-till agriculture were to become the norm. These objectives are addressed using reported values for 6 years of continuous EC measurements over a no-till field located in the heart of the Midwestern Corn Belt (Hollinger et al., 2005) coupled with an analysis of the C emissions associated with conventional- and no-till ecosystems (West & Marland, 2002a).

Materials and methods

Continuous monitoring of C flux related to CO₂ exchange, energy balance, and weather conditions was initiated in August 1996 near Champaign, IL (40.006°N, 88.290°W) as a contribution to GEWEX Continental-Scale International Project (GCIP; Lawford, 1999). The vertical turbulent fluxes of CO₂ sensible and latent heat have been measured using the EC method over a no-till maize and soybean ecosystem from August 1996 to the present. A detailed description of the site characteristics, meteorological measurements, and sampling protocols were provided by Meyers & Hollinger (2004).

During the growing season, missing daytime CO₂ data for 30 min observations from 1 January 1997 through 31 December 2002 were gap-filled based on the light use efficiency (LUE = FCO₂/Rg; FCO₂ is CO₂ flux, Rg is global radiation) computed on a daily basis using all available data for the daylight hours when incoming global radiation exceeded 500 W m⁻². Missing CO₂ flux data for night 30 min periods were backfilled with a respiration function that depends on the soil temperature at 4 cm depth. The function was derived empirically from nighttime data during periods when the average wind speed exceeded 2 m s⁻¹ at the flux measurement height (8 m). The 30 min CO₂ flux data were then summed over each 24 h period beginning at 00:30 hours through midnight local standard time (LST) to obtain the NEE for each day of the year. The data were smoothed by calculating a 5-day running mean. The daily flux data were then summed over the year to determine the annual NEE (metric tons ha⁻¹) of the ecosystem. We define positive values as representing C flux from the ecosystem into the atmosphere, thus a C source, whereas negative values represent C flux into the ecosystem, thus a C sink.

For the no-till agricultural system, values of NEE from EC measurements were combined with estimates of grain C removed from the field (Hollinger et al., 2005) and C emissions associated with agricultural machinery and inputs for conventional- and no-till systems, namely: diesel combustion, fertilizer and pesticide manufacture, and transport of inputs and grain (West & Marland, 2002a). The estimated NEE, grain C (Cgr; kg ha⁻¹), and agricultural C emissions (Cag; kg ha⁻¹) were then used to calculate the NBP of the system as

$$\text{NBP} = \text{NEE} + C_{gr} + C_{ag}. \quad (1)$$

Carbon in the grain was computed as

$$C_{gr} = W_g f_c Y, \quad (2)$$

where Wg is grain moisture content (15.5% for maize and 13% for soybean), fc is the fraction of C in the grain, and Y is yield (kg ha⁻¹). For maize fc is 0.447 and for soybean 0.54 (Loomis & Conner, 1992). Yields from the crops were obtained using a combine yield monitor and total grain weight from the harvest of the same field in which NEE was measured.

Field-level NBP was scaled to the US using published statistics for areas planted in corn and soybean (USDA, 2004). Of the reported land area devoted to crops in the US, only an estimated 10% is managed as a true no-till ecosystem (Derpsch, 2001). NBP (Tg) for no-till maize and soybean agriculture was then estimated from measured NEE and total land area devoted to no-till agriculture. Similarly, NBP was estimated for conventional-till agriculture: however, the NEE + Cgr was assumed to be zero for both corn and soybean (West & Marland, 2002a). For both the conventional- and no-till scenarios, estimates of C emissions associated with agricultural machinery and inputs were used based on the values reported by West & Marland (2002a). Estimates of NBP of the US were then derived by recalculating the no-till
scenario assuming that 100% of the land area was devoted to no-till agriculture. This analysis provides an estimate of the annual NBP that might be expected if all farmers were to adopt a no-till approach to maize and soybean agriculture. The net change in NBP is then determined as the difference between the analysis of the current tillage practices and the hypothetical scenario in which 100% of maize/soybean agriculture is in no-till cultivation.

Results

After 6 years, the NEE measurements indicate a large C sink over the field in which EC measurements were made (Fig. 1). Although 100% of grain is utilized annually somewhere in the world, the C released from grain consumption must be considered when assessing the long-term potential C sink of this system. The mean annual NEE with the grain C component removed is shown to be $-1844 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ for corn (a relatively large sink) and $938 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ for soybean (a C source; Table 1). The grain C removed from the field accounted for majority of the sink observed in the 6 years (cross hatched area; Fig. 1). The C emissions from agricultural machinery and manufacture of inputs are shown to decrease the C sink attributed to corn and increase the source of C for soybean (Table 1). This source of C constitutes a small fraction of NBP compared with the amount stored in grain (shaded area; Fig. 1).

Scaling the field-level results to the US reveals that a sink of over 5 Tg C exists in no-till corn fields but this is offset by almost 3 Tg C released annually from soybean fields (Table 1). Ultimately, however, the land area currently no-tilled constitutes a C flux of $-2.17 \text{Tg}$. The dynamics of C fluxes are much less understood for conventionally tilled fields. We assume in this scenario that the plant/soil system, over time, is C neutral (West & Marland, 2002b). With this assumption, NBP is based only on C associated with agricultural inputs and machinery. These estimates show that conventionally tilled corn and soybean fields release 9.37 Tg annually from fossil fuel use associated with management inputs (e.g. fertilizer, pesticides, machinery; Table 1). Current agricultural practices result in a net C source into the atmosphere of over 7 Tg annually (Table 2). Analysis of C fluxes assuming complete implementation of no-till agriculture for the maize/soybean ecosystem demonstrates a potential annual sequestration of over 21 Tg C (Table 1). Complete conversion of this ecosystem to no-till cultivation could potentially result in a net increase of C sequestration of almost 29 Tg C (Table 2).

Discussion

The objectives of this study were to (1) determine whether the corn/soybean ecosystem has potential to sequester C when all major C fluxes with the ecosystem are considered and (2) estimate the sequestration potential with a hypothetical scenario in which 100% of the maize/soybean ecosystem in the US is converted to no-till. The sequestration potential is based on estimates of NBP computed from measurements of NEE, yields, and published estimates of C released from agricultural inputs and machinery. The results suggest that current corn and soybean agricultural practices release more C than is removed from the atmosphere, despite 10% of the crop land being in continuous no-till agriculture. Our analysis further suggests that this ecosystem may become a C sink if no-till agriculture were to be implemented on a larger scale.

The sequestration potential of this corn/soybean ecosystem, shown to be over 300 kg C ha$^{-1}$ yr$^{-1}$, is within the range reported in other studies (e.g. Lal, 2001, 2004a–c; West & Marland, 2002a, b; Smith, 2004). The results of this study are based on measured fluxes of C between the atmosphere and the ecosystem whereas previous studies rely on either model outputs or soil-based measurements. A major benefit of EC above other methods includes the temporal and spatial scales of the experiment (i.e. field-level measurements were made over 6 continuous years). The similarity in results between EC and soil measurements demonstrates the
potential for EC as a useful tool to augment other methods for determining sequestration potential.

Using EC measurements for the sake of determining C sequestration potential requires an estimate of C fluxes or/and transport not measured with the EC sensors. The yield data for this ecosystem is widely available for both the field in which the EC measurements were made (Hollinger et al., 2005) and for the country as a whole (USDA, 2004). Carbon emissions associated with standard agricultural practices, namely diesel combustion associated with farm machinery along with fertilizer and pesticide manufacture and transport (Lal, 2004a; West & Marland, 2002a, 2003). It is apparent that the C released from fossil fuels and agricultural inputs are a small fraction of the annual total C flux; however, it decreases the potential C sink by nearly a third (Fig. 1).

The field-scale measurements in this study were used to estimate the total C flux associated with the maize/soybean ecosystem in the US. This scaling exercise assumes that the land-area planted with maize and soybean in the US is similar to the field in which the measurements were made. While this is not likely to be the case, it should be noted that over 80% of the maize/soybean ecosystem is located in the heart of the Midwestern US in an area known as the Corn Belt. This area is characterized by some of the most productive agricultural lands in the world and yield per hectare of both maize and soybean is generally conserved across this region (USDA, 2004). The C flux associated with no-till agriculture, 2.17 Tg yr⁻¹, offsets over a fifth of the CO₂ emitted by conventional till agriculture of this ecosystem (Table 1). Based on these results, the potential may already exist for no-till farmers to participate in C credit trading. Furthermore, the large-scale conversion of agricultural lands are assumed to result in even higher sequestration potential, with net C sequestration of more than 25 Tg C compared with the current practices (Table 1).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Analysis of net biome productivity (NBP) in teragrams (Tg) of C for the maize/soybean agricultural ecosystem in the US</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Agricultural carbon emissions</strong></td>
<td><strong>Inputs</strong> (kg ha⁻¹ yr⁻¹)</td>
</tr>
<tr>
<td>Corn</td>
<td>−1844</td>
</tr>
<tr>
<td>Soybean</td>
<td>938</td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>0</td>
</tr>
<tr>
<td>Soybean</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>100% conversion to no till</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>−1844</td>
</tr>
<tr>
<td>Soybean</td>
<td>938</td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented based on area planted with maize and soybean for the years 1997–2002 and assuming 10% of agricultural land was not tilled. Net ecosystem exchange (NEE) from the no-till analysis was collected using eddy covariance measurements and averaged over 3 years for each crop species and Cgr represents the grain carbon removed from the field. For the conventional-till analysis, NEE is assumed to be zero (West & Marland, 2002a, b). Also included is an analysis for 100% conversion of the same land area to no-till agriculture. Estimates of conventional NEE and carbon emissions associated with agricultural inputs and machinery are from West & Marland (2002a, b). Positive values represent fluxes from the ecosystem to the atmosphere.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The net biome productivity (NBP) summed for current corn/soybean agricultural ecosystems with 10% of agricultural land in no-till and for a future hypothetical scenario where 100% of corn/soybean agriculture is in no-till</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current practices</td>
<td>NBP (Tg)</td>
</tr>
<tr>
<td>No till</td>
<td>−2.16</td>
</tr>
<tr>
<td>Conventional till</td>
<td>9.37</td>
</tr>
<tr>
<td>Total</td>
<td>7.21</td>
</tr>
<tr>
<td>Future scenario</td>
<td></td>
</tr>
<tr>
<td>100% no till</td>
<td>−21.65</td>
</tr>
<tr>
<td>0% conventional till</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>−21.65</td>
</tr>
<tr>
<td>Net potential sequestration</td>
<td>−28.86</td>
</tr>
</tbody>
</table>

Net potential sequestration is the net change in C flux between the two scenarios. Positive values represent fluxes of carbon from the ecosystem to the atmosphere.
Despite these analyses, this ecosystem may have a finite C sequestration potential after conversion to no till (Lal, 2004c). The limited sequestration potential of this system has been marketed as a bridge between present-day practices and the development of cleaner fuel sources and technologically advanced methods of sequestering C (e.g. Lal, 2004c). While our study supports the notion that C sequestration potential exists with the adoption of no-till agriculture, it should be noted that the net C sequestration with complete conversion to no-till maize/soybean agriculture (28.9 Tg; Table 2) represents a small fraction of the nearly 1600 Tg C emitted in the form of CO₂ for the US as a whole (EPA, 2004). While conversion to no-till might sequester less than 2% of the total CO₂ emissions of the US, no-till agriculture might be considered one of many steps in which agriculture as a whole might sequester C (e.g. Lal et al., 1999). Further, consideration of other greenhouse gas emissions must be considered when assessing the impact of no-till agriculture on global warming potential (Six et al., 2004).

The conclusions of this study further support the numerous other environmental and economic benefits associated with no-till agriculture (Uri, 2000). However, the purpose of these agricultural systems needs to be evaluated based on what they are intended to do, namely: provide agricultural products for sustenance. The potential for altered crop yields associated with no-till practices must also be considered (Sims et al., 1998). If the primary focus of agricultural lands is to sequester C to offset anthropogenic C emissions, then alternative crop systems may be more suitable for sequestering larger amounts of carbon. Such alternative crop systems may include a switch to bio-fuel crops (Heaton et al., 2004); a cover crop in the soybean year or replacement of soybean in the maize/soybean rotation with a crop that produces greater vegetative biomass; adopting practices that encourage deep rooting of crops plus the movement of C and nutrients deep into the soil profile (Krug & Hollinger, 2003); or reverting crop lands to their presettlement prairie state (Krug & Hollinger, 2003). With regard to a C credit scenario as established by the Kyoto Protocol, the results obtained in our study suggest that conversion to no-till agriculture may help to support the profitability of C credits for farmers, but the amount of C potentially sequestered is limited to a small fraction of annual emission within the US.

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