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Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques

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Abstract

There is much interest in the role that agricultural practices might play in sequestering carbon to help offset rising atmospheric CO_2 concentrations. A number of management methods that might increase soil C levels have been suggested, but there are scant available data to properly support recommendations or policy changes. We have used eddy covariance measurements of net ecosystem exchange (NEE) in contrasting management systems to discern the impact of two specific practices, reduced tillage and a spring cover crop in the soybean year, on the biennial C balance of a corn/soybean rotation, the dominant cropping system in much of the midwestern United States. Measurements commenced in fall 2001, immediately following corn harvest and tillage, and continued through a year of soybean and a year of corn. One of the two fields was farmed conventionally (CONV), with fall chisel/disk tillage after each harvest, soybean planting in late May (2002), and corn planting in early May (2003). In the alternative field (ALT), we used reduced tillage (strip till) each fall following harvest, and a spring oats cover crop in the soybean year (2002) that was planted in early April, then killed with a herbicide shortly after soybean planting. Both fields have the same soil type, and were similarly instrumented, with a sonic anemometer and open-path infrared gas analyzer. Reduced tillage resulted in somewhat lower soil respiration rates in both autumns in ALT, relative to CONV. Also, the spring oats cover crop prior to soybean did fix additional C, but it was rapidly respired after the oats were killed, and the surface crop residue slowed the initial development of the subsequent soybean crop. Soybean yields for the two fields were similar, but slightly higher for CONV, a pattern that was more pronounced with corn the following year. Overall, cumulative NEE was larger (more C fixed) in the conventional field, but C removed in yield in the conventional field was larger too, so that the apparent change in soil organic carbon (ΔSOC), estimated as NEE – harvested C, in the two fields was nearly identical. In both treatments the apparent ΔSOC was negative (approximately 90 g C m^{-2} SOC lost over the biennium, or about 20% of cumulative NEE) but this may be at least partially due to systematic underestimation by eddy covariance rather than an actual loss of SOC. We

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conclude that neither of these management practices (reduced tillage, spring cover crop) resulted in any C sequestration within the first two years of implementation that is resolvable with current measurement methods.
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Keywords: Carbon balance; NEE; Cover crop; Strip tillage; Sequestration; Corn-soybean rotation

1. Introduction

Consensus among scientists around the world is that increasing atmospheric CO_2 concentration is causing global average temperatures to rise, and that this may have substantial negative impacts, particularly if it occurs rapidly. Consequently, there is intense interest in finding ways to damp projected changes by adopting policies and strategies that alter local rates of surface/atmosphere carbon exchange in ways that favor increased surface storage. The possible role of agriculture in this effort is an interesting question. It is generally accepted that agriculture has historically been a contributor to the debit side of the terrestrial carbon ledger. Land use changes, primarily expansion of annual cropping systems into forests and grasslands, are deemed responsible for 20–25% of the increase in atmospheric CO_2 that has occurred over the past 150 years (Lal et al., 1998). In the Midwestern United States, clearing and repeated plowing of soil is estimated to have caused the oxidation of 30–50% of the organic matter present prior to cultivation. However, changes in farming practice, primarily the adoption of less aggressive forms of tillage, appear to have arrested this decline (Allmaras et al., 2000).

The very fact that so much soil carbon was lost is now viewed positively by some, in the sense that it may represent a reservoir that can be refilled through the adoption of appropriate farming practices (Lal et al., 1998). Others have questioned this optimism (Schlesinger, 2000), suggesting that potential carbon sequestration in agricultural systems is likely relatively insignificant, particularly when all greenhouse gas costs (e.g. fertilizer, fuel) are considered. The prevailing policy view appears to be that agricultural ecosystems are more or less in carbon stasis. Hence the major carbon flux networks that have been established, such as AmeriFlux (Baldocchi et al., 1996), Fluxnet Canada (http://www.fluxnet-canada.ca/participants.html-), and CarboEurope (Aubinet et al., 2000), have largely focused on natural ecosystems.

There are, however, some compelling reasons to examine this question in more detail. Farm fields are intensively managed ecosystems, so there may well be readily viable avenues for effecting changes in their carbon balance. If appropriate practices are identified they can be encouraged through a legislative and regulatory framework that is already in place – in fact there is precedent for this in the United States and many other countries, where farm support programs have been used to encourage cropping methods that reduce soil erosion or improve water quality. Agriculture enjoys broad political support in nearly every country, so if it is an integral part of carbon sequestration policy, chances for public and governmental acceptance will likely improve.

One particular cropping system, a biennial rotation of corn (*Zea mays* L.) and soybeans (*Glycine max* L.), is significant because it is the primary rotation throughout the Midwestern United States. While still highly productive, soils of this region have lost a substantial portion of their pre-settlement organic carbon through the oxidative effects of moldboard plowing and tile drainage, and the replacement of perennial trees and grasses with annual row crops. However, as mentioned earlier there are indications that these losses have leveled off in the latter part of the twentieth century (Allmaras et al., 2000), hence the hope that changes in farming practices might be able to sequester carbon by restoring soil organic matter. In recent years corn has been planted on approximately 33 million ha of land in the United States, and soybeans on about 30 million ha. Much of this land area overlaps, since corn and soybeans have similar climatic adaptation, and rotation is commonly employed to reduce the weed and insect pressures that generally increase if either is planted year after year. The focus of our paired-field approach is to test farming practices that are thought to have the potential to increase the net carbon balance of this agroecosystem, the biennial corn/soybean rotation.

The carbon balance for an agricultural field over a time period of interest from t_1 to t_2 can be written as

$$\int_{t_1}^{t_2}(\mathrm{NEP})\,\mathrm{d}t - \int_{t_1}^{t_2}\frac{\mathrm{d(SOC)}}{\mathrm{d}t}\,\mathrm{d}t - \int_{t_1}^{t_2}Y[C_\mathrm{f}]\,\mathrm{d}t + \int_{t_1}^{t_2}(C_\mathrm{d}-C_\mathrm{e})\,\mathrm{d}t + \int_{t_1}^{t_2}P([\mathrm{DIC}])\,\mathrm{d}t - \int_{t_1}^{t_2}R([\mathrm{DOC}]+[\mathrm{DIC}])\,\mathrm{d}t - \int_{t_1}^{t_2}J([\mathrm{DOC}] + [\mathrm{DIC}])\,\mathrm{d}t = 0 \qquad (1)$$

where NEP is the net ecosystem productivity (equal, but opposite in sign, to net ecosystem exchange, NEE), SOC is the soil and detrital organic C on a mass per unit area basis, Y is the harvested mass per unit area with a fractional carbon content C_f, C_d and C_e are rates of carbon deposition and removal in particulate transport, P is precipitation rate, R is runoff rate, and J is drainage rate, with mean concentrations of dissolved organic carbon, DOC, and dissolved inorganic carbon, DIC. The precipitation component is trivial and generally ignored. The drainage and runoff components are also considered to be trivial (somewhat hopefully, since they are difficult to measure) in most cases. Under such circumstances, Eq. (1) can be reduced and rearranged to

$$\int_{t_1}^{t_2}\frac{\mathrm{d(SOC)}}{\mathrm{d}t}\,\mathrm{d}t = \int_{t_1}^{t_2}(\mathrm{NEP})\,\mathrm{d}t - \int_{t_1}^{t_2}Y[C_\mathrm{f}]\,\mathrm{d}t \qquad (2)$$

The choice of an appropriate time period for integration is not a trivial question. The term on the left side of Eq. (2) encompasses a complex suite of biological and chemical reactions, each with their own characteristic kinetics. Presumably, if steady conditions (climate, vegetation, management) are maintained for a suitably long time, inputs match outputs and changes in SOC are negligible, but whenever the system is perturbed in a way that affects either the input of fresh material or the reaction rate constants, then SOC will change. If a step change in management is imposed (e.g. a switch in tillage or crop type) and the various decay processes are first order reactions, one would expect the change in SOC to be largest initially before declining toward nil as a new equilibrium is reached. The actual situation is considerably more complicated since there are seasonal and inter-annual variations in weather, unpredictable perturbations from pests and diseases, and potential feedbacks on productivity from changes in SOC, all of this superimposed on long-term changes in atmospheric CO_2 concentration.

Direct measurement of changes in SOC requires soil sampling. This poses a number of problems, foremost among them a low signal to noise ratio. Likely changes in soil C storage are quite small relative to the amount of carbon present in many soils, a problem that is compounded by soil spatial variability, the labor intensive nature of soil sampling, and the cost of laboratory analysis. Such studies may require a decade or more before differences can be discerned (Robertson et al., 2000), making them difficult to conduct and even more difficult to fund. Furthermore, they require an arbitrary choice of sampling depth, which in some cases has been as shallow as 7.5 cm (Robertson et al., 2000), excluding from consideration any C accretion or loss that occurs below that depth. Finally, since their temporal resolution is poor, soil-based measurements offer little insight into causes and effects or underlying processes.

What about the other components in Eq. (2)? A useful feature of agricultural fields is that grain yield is measured with considerable accuracy since income depends on it, and mean grain C content can be readily determined in the laboratory. Direct measurement of NEE is more difficult, and entails the use of micrometeorological methods, typically either eddy covariance or a gradient-based technique. Temporal resolution of such measurements is superb (on the order of half-hourly), but integration over a full 2-year rotation requires many thousands of measurements. Unfortunately, gaps are inevitable. Some data are missed due to instrument failures, power outages, and the like. Other data must be discarded because key measurement assumptions, such as stationarity of turbulence or the absence of advection, are in question. As a consequence, the end sum of NEE from these sites depends to a considerable degree on the gap-filling strategies that are used (Griffis et al., 2003; Falge et al., 2001).

1.1. Management options

Tillage is the most commonly mentioned route for altering the C balance of row crops like corn and soybeans; many sources (e.g., Paustian et al., 1997; Uri, 2001) have reported or projected impressive accrual of soil carbon in no-till systems, in which crops are planted into the stubble and residue of the previous year with no plowing or cultivation. West and Post (2002) have analyzed a large number of long-term tillage trials in which changes in soil organic matter have been measured and conclude that conversion from moldboard plowing to no-till can sequester 57 ± 14 g C m^{-2} per year. It is difficult to extrapolate these results to a regional scale for a couple of reasons. First, moldboard plowing is no longer the standard, conventional form of tillage; many farmers have already abandoned it in favor of less intrusive tillage tools, such as the chisel plow. Secondly, farmers have been reluctant to adopt complete no-till in the northernmost portions of the corn belt, because it generally causes a reduction in yield. This is traceable to slower seedling emergence and sluggish early season growth. No-till fields are slower to warm in the spring, primarily due to the higher albedo of crop residue relative to a plowed bare soil. A hybrid approach that has shown considerable promise is known as strip tillage. It involves a fall tillage operation in which only a narrow strip in the center of each row is tilled, leaving the remaining residue in place. In the spring, seeds are planted into the bare, tilled strips. Several years of field tests at Waseca, MN have shown that seed zone temperatures, seedling emergence, and yields for strip-tilled fields are similar to conventionally tilled fields and generally superior to no-till (Vetsch and Randall, 2002). There are no reports of the impact of strip tillage on carbon balance, but presumably it should exhibit a considerable measure of the putative merits of no-till, since much of the soil and crop residue is left undisturbed. Thus, realizable carbon gains may not match those reported in the literature, because many, if not most, farmers in the upper Midwest would be converting from chisel plowing or something similar (not from moldboard plowing) to strip tillage or other variations of no-till.

A second area of opportunity for increasing the net carbon balance of a corn/soybean rotation is *cover cropping*. Under midsummer conditions corn is remarkably efficient in converting CO_2 and solar energy into grain, a legacy of many centuries of selection and breeding. But it is a warm-season species, virtually dormant below 10 °C, with no tolerance for frost. Hence it is not planted until spring is well under way (typically early May in southern Minnesota), and farmers plant cultivars that are bred to produce their grain quickly, then lapse into senescence prior to any likelihood of frost. Soybeans are planted even later than corn and have lower midseason light use efficiency, with a similar aversion to frost. As a result, a substantial amount of photosynthetically active radiation is unused in corn/soybean cropping systems, particularly in the spring of the soybean year. For example, Fig. 1 shows mean daily solar radiation and air temperature measured over the past thirty years at St. Paul, MN. The data points plotted are midday NEE that we have measured at Rosemount, MN (20 km south of St. Paul, MN) for oats (1995), corn (2000), and soybean (2002). It is clear that if soybean is grown without a prior cover crop, as is the case for almost all of the 2.9 million ha grown annually in Minnesota, a substantial amount of available PAR will be unused. In essence, under current practice this is a fallow period, and numerous long-term studies (McGinn and Akinremi, 2001; Campbell et al., 1998; Halvorson et al., 2002) have shown that SOC levels are inversely related to frequency or length of fallowing.

Cool-season cereal grains such as oats, wheat, and rye are adaptively suited to the high radiation, low temperature conditions that prevail in the spring. Some species, such as cereal rye and winter wheat, can even be planted in the fall following harvest, so that they can also use some of the otherwise unused PAR available in the fall. However, this is often impractical due to the need to delay corn harvest until the grain has dried sufficiently for storage and processing. Timely planting of spring cover crops, such as oats, can also be a problem if soils are too wet to sustain wheel traffic, but in years and locations where planting is possible, the additional carbon gain might justify the expense, with the additional, widely recognized benefit of protection of the soil surface against erosion during spring rains.

The purpose of this experiment was to examine the combined effects of reduced tillage and a spring oats cover crop (prior to soybean) on the carbon balance of a corn/soybean rotation. We have taken the approach of measuring in differential mode, comparing two different farming systems by making simultaneous, or paired, flux measurements (NEE) in each of them. Amiro (2001) used this approach to compare a forested area with a nearby burn site. In our case we wish to contrast two farming strategies in fields that

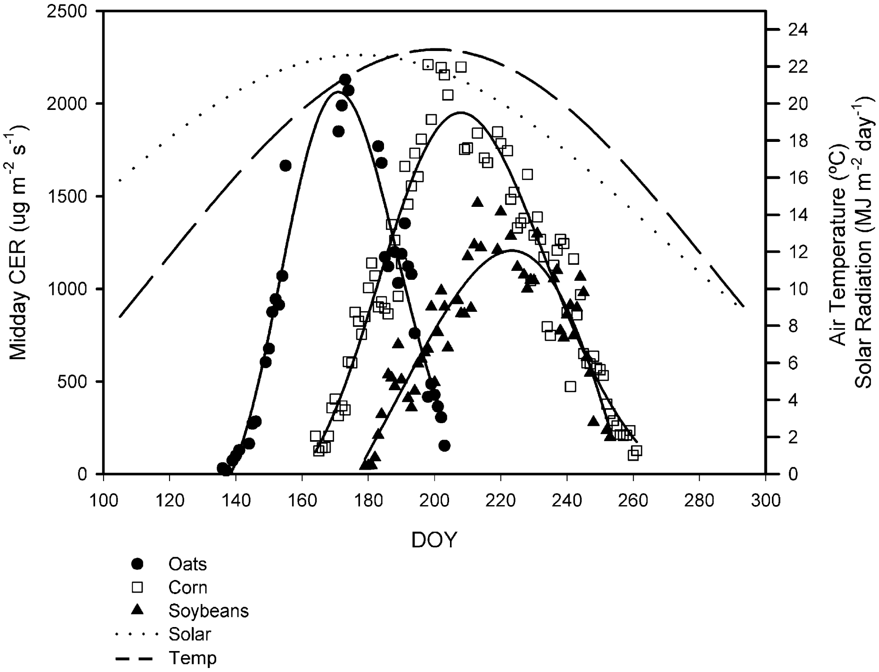

Fig. 1. Mean daily solar radiation (dotted line) and mean air temperature (dashed line) computed from long-term measurements at St. Paul, MN. Individual data points represent midday NEE measured at Rosemount, MN for oats (1995), corn (2000), and soybean (2002).

are immediately adjacent to one another, with the same soil types and similar long-term cropping histories, and subjected to the same synoptic weather conditions. Instrumentation, data collection protocol, and analytical procedures in the two fields are identical. In addition, we have also measured the other components of the C balance, yield (Y) and SOC, in each field. Through this we hope to obtain insights into the *differences* in carbon balance between the systems, despite the uncertainties in the cumulative absolute values of each. Continuous measurements of carbon exchange rate have been made since November 2001 in the two fields, one farmed conventionally, the other farmed with reduced tillage and with a spring cover crop in the soybean year of the biennial rotation.

2. Materials and methods

2.1. Site description

The fields in which this research was conducted are at the University of Minnesota's Rosemount Research and Outreach Center, approximately 25 km south of St. Paul, MN. The area was a glacial outwash plain in the late quaternary that was subsequently covered with loess, creating soils typified by a silt loam surface layer of 0.5–1.8 m overlying a thick (>20 m) layer of sand and gravel. A wide array of soil and meteorological data has been collected at this site for a number of years in support of research endeavors (e.g., Baker et al., 1992; Spaans and Baker, 1995; Flerchinger et al., 1996; Koren et al., 1999). The two fields are directly adjacent but separated by a road. The south field (designated CONV) was farmed conventionally, which in this area means a corn/soybean rotation, with fall tillage that consisted of a chisel plow in combination with a tandem disk. Fertility was maintained with spring preplant applications as dictated by soil testing. The north field, hereafter identified as ALT, was also in corn/soybean rotation, but for this experiment there were two modifications designed to improve net carbon balance. First, tillage intensity was reduced by using strip tillage instead of chisel plowing following corn harvest in fall 2001 and soybean harvest in fall

2002. Secondly a cover crop of oats was planted in early spring 2002 (DOY 108) and allowed to grow for approximately 7 weeks. Soybeans were planted directly into the oats on DOY 150, the same day that they were planted in CONV (fallow to that point). The oats in ALT were sprayed on DOY 160 with glyphosate, a broad spectrum herbicide. The emerging soybeans, a cultivar with genetically engineered glyphosate resistance, were unaffected. The CONV field was also sprayed with glyphosate to control weeds.

At the conclusion of the 2002 growing season both fields were harvested on DOY 290 and 291 with a combine equipped with a yield monitor and GPS. Following harvest, tillage was delayed for 3 weeks due to a combination of inclement weather and the need to finish harvesting other fields. On DOY 311 the CONV field was tilled with a disk/ripper, which produces results similar to a chisel plow followed by a disk. The ALT field was strip-tilled, a form of reduced tillage described earlier. Flux measurements were made continuously through this period, although some ancillary measurements, such as soil heat flux, had to be briefly discontinued as equipment was removed prior to tillage and reinstalled afterward. Measurements continued through the winter and the following growing season. The winter of 2002–2003 in Minnesota was near normal in most respects, with somewhat less than normal snowfall. The soil profile was completely thawed by DOY 115, 2003, and corn was planted in both fields on DOY 122. The conventional field was disked prior to planting, while in ALT the corn was planted directly into the strip-tilled rows established in fall 2002. ALT was fertilized with 112 kg N ha^{-1} surface-applied as urea, while CONV was fertilized with 134 kg N ha^{-1}, applied by injection as NH_3. The higher rate was necessary to compensate for the greater volatilization losses that are expected with anhydrous ammonia. A pre-emergence herbicide (metolachlor) was applied to both fields. Corn emergence was similar in the two fields, but following emergence the ALT field developed a serious infestation of shepherd's purse (Capsella bursa-pastoris). Consequently it was necessary to apply an additional herbicide treatment (atrazine). The summer of 2003 began with ample moisture and favorable temperatures, but a moderate drought developed in midsummer, with only 5.5 mm of rain falling between DOY 195 and 218. Fortunately, 20 mm of rain fell on DOY 218, and subsequent rains were sufficient to keep pace with evaporative demand until harvest on DOY 289.

2.2. Flux measurements

A 10 m tower was located in the center of each field. Each has fetch of 180 m or more in all directions, and each was instrumented with a three-dimensional sonic anemometer (CSAT 3, Campbell Scientific Inc., Logan, UT) and an open-path infrared gas analyzer (LI7500, LiCor, Lincoln, NE) mounted on a boom that was adjusted as crop height changed. Net radiation was computed by separately measuring solar and longwave radiation with pyranometers and pyrgeometers (Eppley Laboratories, Newport, RI). The upward-facing instruments were continuously ventilated to minimize condensation and precipitation effects. Soil heat flux was measured with an array of heat flux plates (Hukseflux, the Netherlands and REBS, Seattle, WA) installed at 10 cm, with thermocouples in the soil above to calorimetrically compute the contribution from the surface layer. Soil moisture in the surface layer was measured by an automated time-domain reflectometry system (TDR 100, Campbell Scientific, Logan, UT) to permit calculation of heat capacity. Additionally, soil water content was measured at 8 depths from 0.05 m down to 1 m. All soil and radiation variables were measured at either 30 s or 60 s intervals and then averaged or computed at 30-min intervals, with the exception of the profile water content measurements, which were made once every 30 min. The eddy covariance instruments were sampled at 10 Hz, with covariances calculated every 30 min. The calibration of the open-path gas analyzer was checked at regular intervals, using a calibration cell provided by the manufacturer. A standard gas was used to set CO_2 span, and a dew point generator (Li-610, Licor, Lincoln, NE) was used for the H_2O span, while zeros were checked for both gases by scrubbing an airstream with magnesium perchlorate and soda lime (LI-670 flow controller, Licor, Lincoln, NE).

2.3. Data handling procedures

Post-processing of the data included 2D coordinate rotation, followed by determination of latent and sensible heat fluxes from the measured fluctuations in vertical wind, sonic temperature, and vapor density. This involved simultaneous solution of equations incorporating the Webb et al. (1980) density corrections and the Schotanus et al. (1983) derivation of sonic temperature. The latter equation was modified for the case where the instantaneous measurements of T have already been corrected for cross-wind contamination. The latent and sensible heat fluxes were then used to compute a density-corrected NEE from the mean covariance of vertical wind speed and carbon dioxide concentration.

In situations where meteorological flux data are collected there are inevitably problems with either missing or questionable data. The former are simpler problems in most respects. Missing data, due to power outages, equipment failures, maintenance, or field operations, are unambiguously identifiable by their absence. Subsequent analysis can be conducted with explicit recognition that data are missing, or surrogates for the data can be generated with gap filling procedures (Falge et al., 2001). Questionable data present a more difficult problem. It is a challenge to define screening procedures that will defensibly and objectively remove nonsense data while minimizing the highly undesirable excision of valid data.

We found that essentially all occurrences of anomalous data were associated with low turbulence, precipitation, or condensation (dew or frost). Consequently, we screened the data to remove all time periods when u_* was less than 0.1 m s^{-1} or relative humidity exceeded 98%. Our cutoff for excluding low u_* data is lower than others have used above forested canopies (e.g. Barr et al., 2002). We applied conventional gap-filling procedures to allow the generation of year-long estimates of NEE. For growing season photosynthetic fluxes, the screened data were used along with coincident PAR measurements to compute Michaelis-Menten coefficients for 2–5 day windows through each growing season. These were then used to estimate NEE for those half-hourly periods for which data were missing. Gaps in the positive NEE (respiration) data were filled by fitting subsets of the screened flux data to polynomial regressions against 5 cm soil temperature.

Midway through the experiment we were informed by the manufacturer of a timing error in the open-path gas analyzer (Licor application note, June 2003). Detailed analysis of 10 Hz time series showed that this had resulted in underestimates of the covariances that ranged between 5 and 13%, with a mean underestimate of 8%. All data that had been collected to that point were therefore adjusted by a factor of 1.08, and the software upgrade provided by the manufacturer was installed in the analyzer to eliminate subsequent errors.

3. Results and discussion

Daily NEE values for the entire 2-year period for both fields (Fig. 2a) were computed from a mixture of approximately 70% measured flux data and 30% 'virtual' data generated with the gap filling algorithms. The latter were scattered throughout the 2-year period; seasonally they occurred with greater frequency in the winter, and diurnally there were more at night. Both weak turbulence and condensing conditions are more often nocturnal phenomena. Superficially, the data for the two fields look quite similar, both showing the much higher photosynthetic capacity of maize relative to soybean. Subtracting one signal from the other (Fig. 2b) more clearly shows the points in the biennium at which important differences exist between the two systems.

3.1. Tillage effects

There was greater C loss from the conventional (chisel/disk) field than from the strip-tilled field between fall tillage and the onset of winter in both years of the rotation. For both years, the cumulative difference between the two treatments during the post-tillage, pre-freezing period was approximately 10 g m^{-2}. Fig. 3a shows the daily NEE for each field during this period in 2002. A brief increase in CO_2 emission occurred for a few days following tillage in both fields, but the magnitude of the fluxes is far below the tillage-associated bursts reported from chamber-based measurements (Reicosky, 1997). The difference between treatments did not persist in the spring (Fig. 3b). The mean daily NEE during this period for the CONV and ALT fields were 1.30 ± 0.40 and 1.23 ± 0.39 g m^{-2}, respectively. The difference between these means is not significant, even at a 50% confidence level.

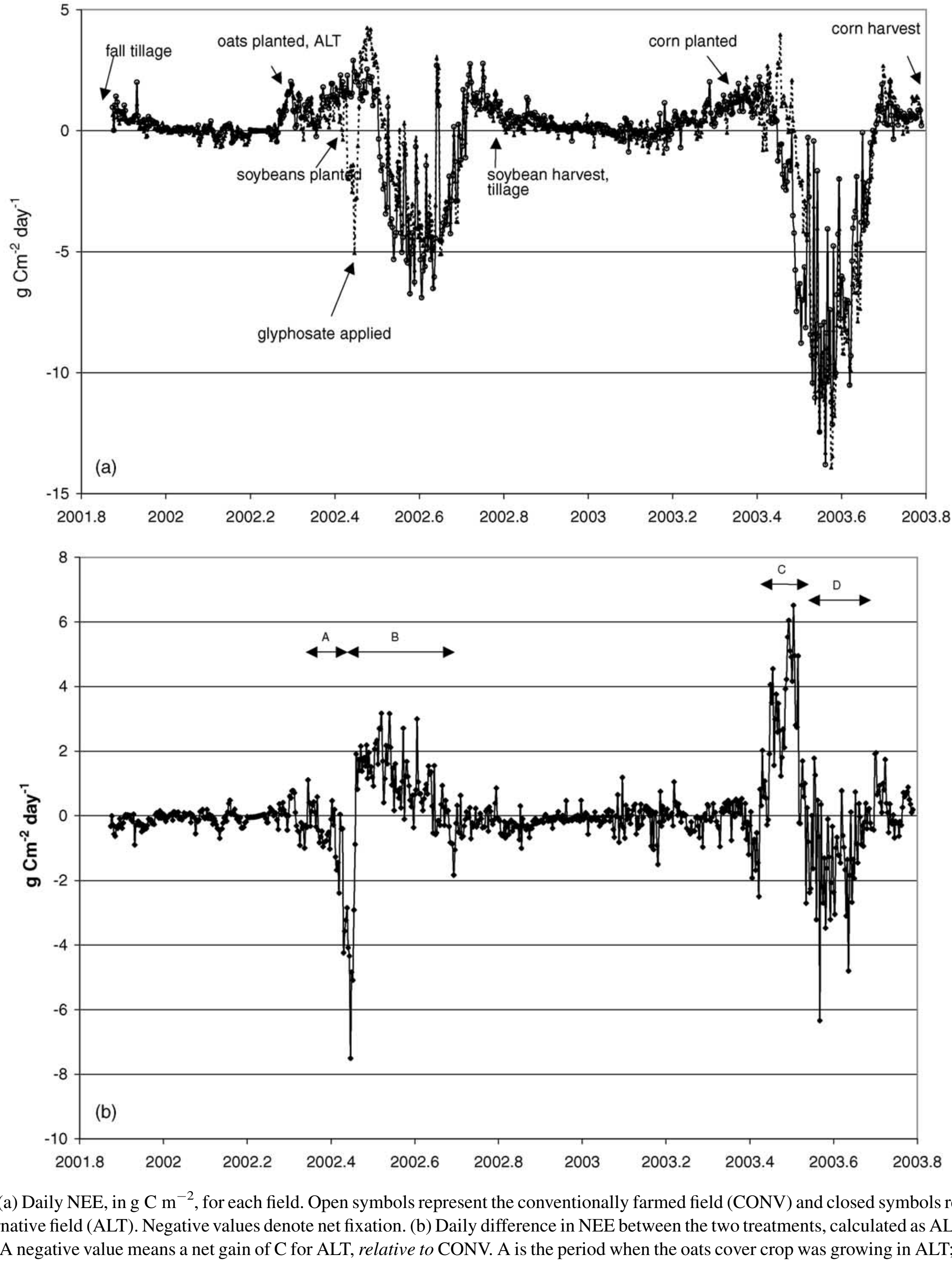

Fig. 2. (a) Daily NEE, in g C m^{-2}, for each field. Open symbols represent the conventionally farmed field (CONV) and closed symbols represent the alternative field (ALT). Negative values denote net fixation. (b) Daily difference in NEE between the two treatments, calculated as ALT minus CONV. A negative value means a net gain of C for ALT, *relative to* CONV. A is the period when the oats cover crop was growing in ALT; B is the period when the oats were dying and soybeans were emerging; C is the early part of the growing season in 2003, when the corn in ALT was delayed relative to CONV, due to lower soil temperatures and weed pressure; D is the mid to latter part of the 2003 growing season, when ALT recovered from its poor start. (c) Cumulative NEE for each treatment, and cumulative difference between the two, in g C m^{-2}. The dashed line is the conventionally-farmed field, the light solid line is the alternative field, and the heavy solid line is the difference.

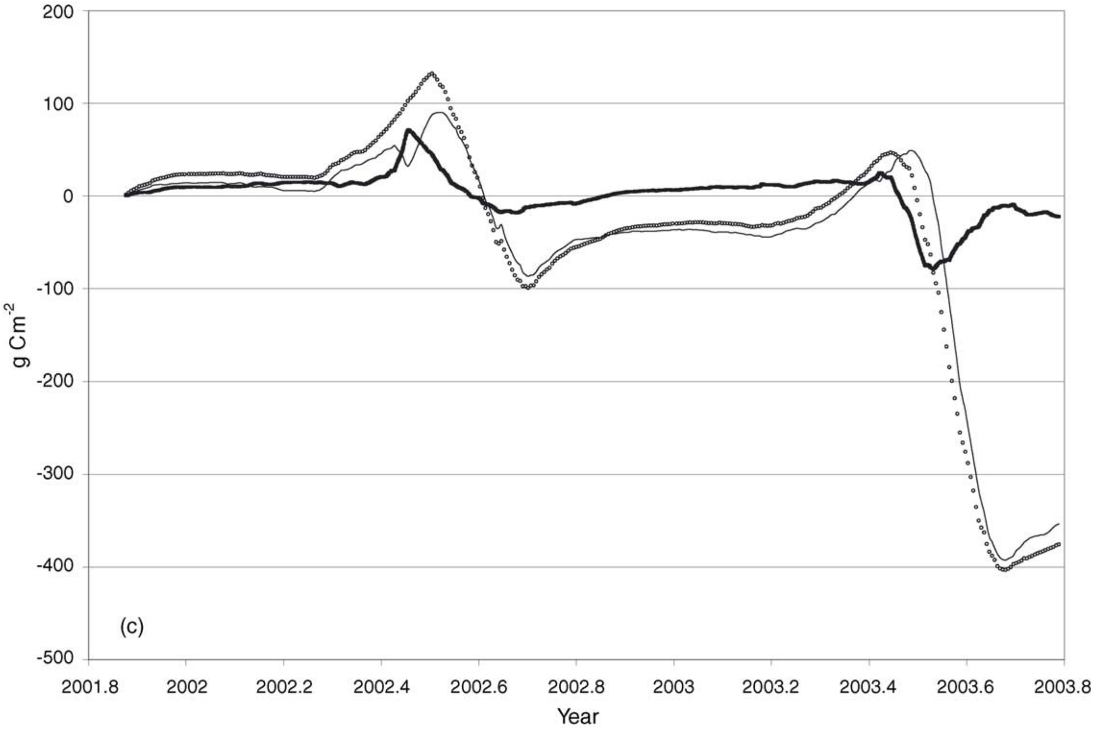

Fig. 2. (*Continued*).

One negative impact of reduced tillage that was subsequently manifested was an increase in weed pressure in the spring of 2003. The early growth of the corn in ALT was inhibited by an infestation of shepherd's purse (*Capsella bursa-pastoris*), while there was no weed problem in the conventionally tilled CONV. Control was established with herbicide application, but there still was a delay in development of the crop (Figs. 2b and 4). Fortunately the crop was able to recover and the impacts on yield and NEE were small. In fact ALT compensated for its poor early season growth by outperforming CONV during the latter part of the growing season (Fig. 2b).

3.2. Cover crop

The impact of the spring cover crop prior to soybeans (2002) in ALT is seen in Fig. 2b in the large downward spike in the early part of the 2002 growing season (DOY 156–167). It is also evident in the higher respiration losses from ALT relative to CONV in the weeks following soybean planting and glyphosate application (DOY 150 and DOY 160, respectively). Much of the relative C gain of ALT from the oats photosynthesis disappeared rapidly, via higher respiration of the decaying oats residue and through diminished early season soybean photosynthesis, presumably due to the shading effects of the crop residue. Initially the soybeans developed more slowly in ALT, but recovered to produce yields only slightly lower than those in CONV. In general, the addition of a spring oats cover crop provided no benefit in the form of C sequestration. It must be added that due to an unusually cool spring, the oats had been planted later than desired, resulting in somewhat less oats biomass production than would typically be expected. However, Fig. 4 suggests that any C fixed in an additional week of oats growth would simply have resulted in higher subsequent respiration, with little impact on annual C balance unless it were accompanied by a change in C allocation toward more recalcitrant compounds. A fall cover crop, such as winter rye or winter wheat, might be more beneficial, because it would get a much earlier start in the spring and

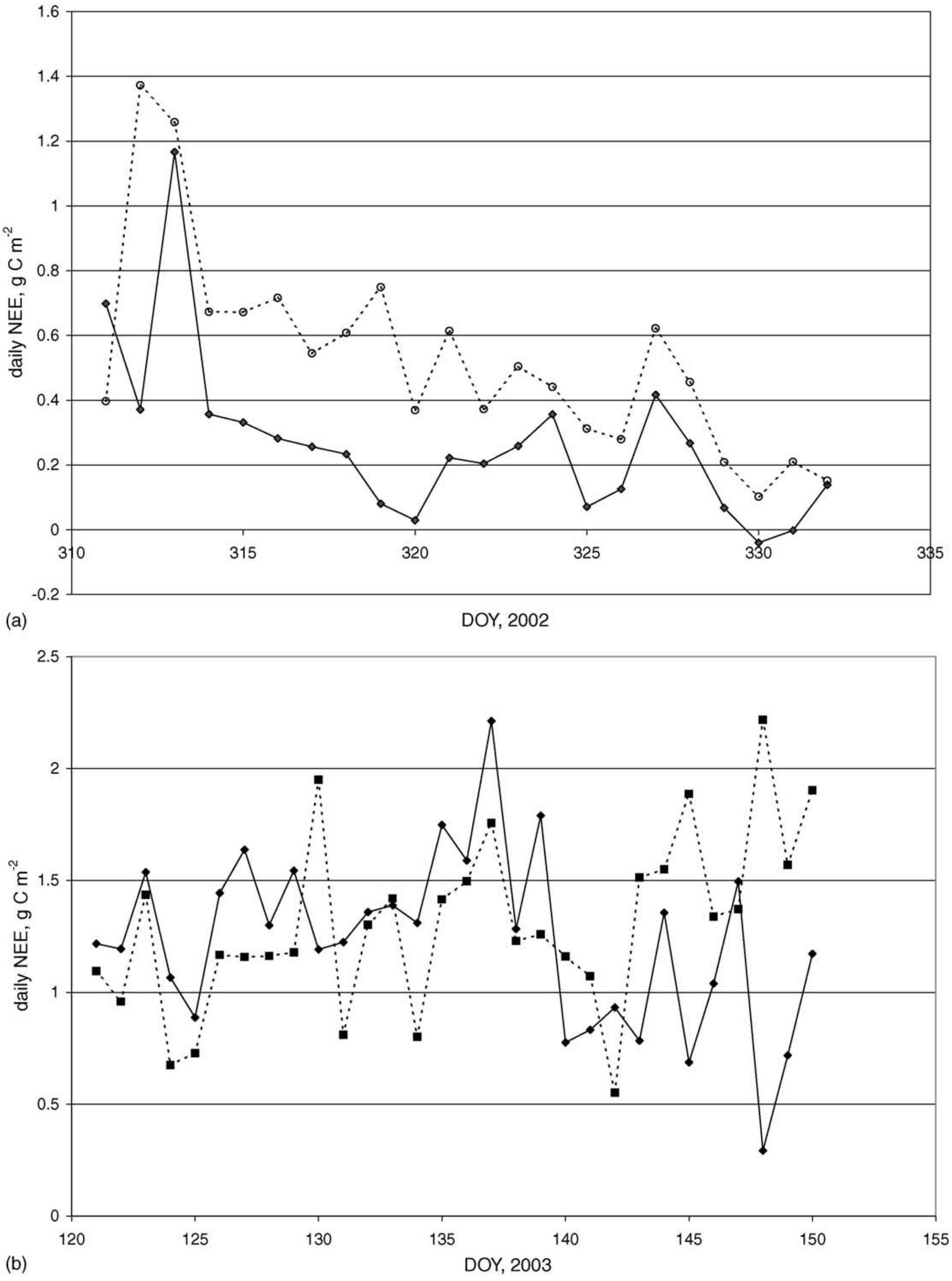

Fig. 3. (a) Daily NEE during the period following tillage in fall 2002. The conventional field (open symbols) was plowed with a disk/ripper (equivalent to a chisel and tandem disk) and the alternative field was strip-tilled, a form of modified no-till in which only a narrow band in each row is tilled. Both fields were tilled on DOY 311. (b) Daily NEE for the same fields during the following spring (2003).

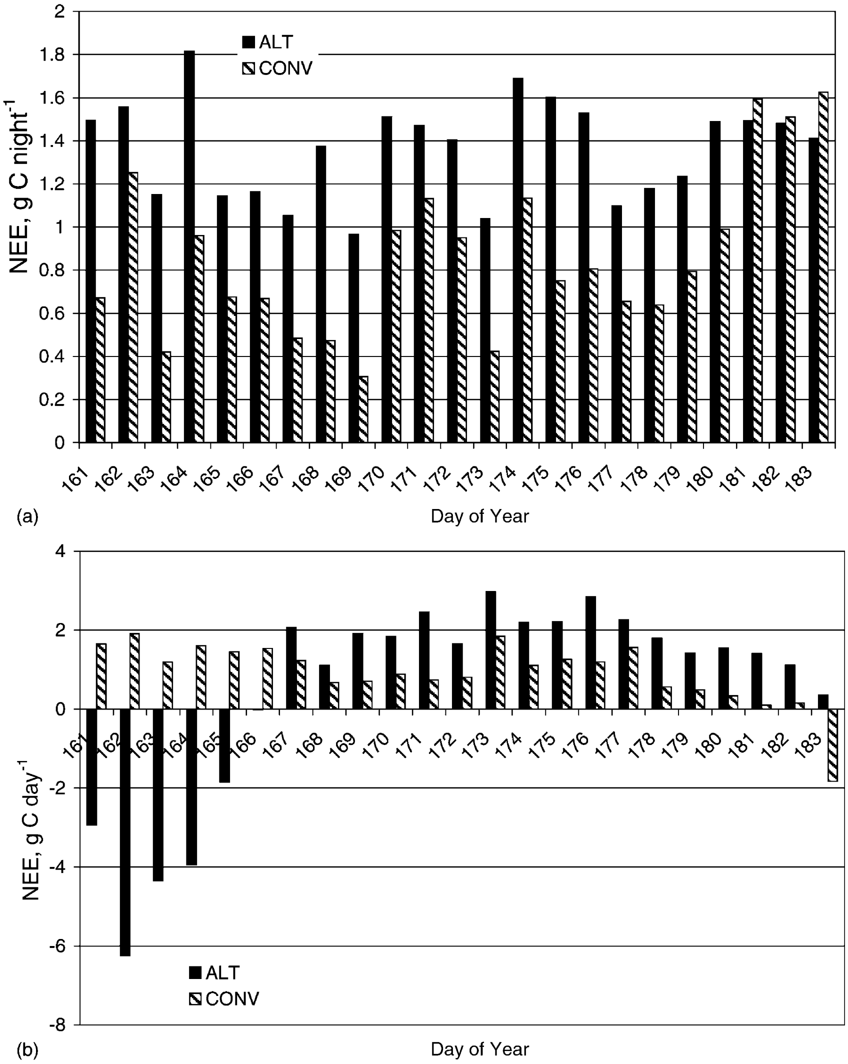

Fig. 4. Bar graphs showing nighttime (a) and daytime (b) NEE for each field during the period immediately following glyphosate application to both fields on day 161. The solid bars are ALT and the shaded bars are CONV.

proceed further toward physiological maturity prior to soybean planting.

3.3. Overall C balance

Yield was measured in both years with a combine equipped with a GPS and yield monitor; for the purposes of this analysis we computed mean yields for the area within 100 m of each mast for each year. The C removed in the maize harvest was more than double that removed in the soybeans. The differences in overall yield between the two treatments are consistent with the differences in NEE (Table 1), such that the respective ratios of NEE to harvested C over the 2-year rotation are essentially identical.

The data are presented graphically in Fig. 5, arbitrarily divided into a soybean year and a corn year, with each year beginning at the point of seedling emergence. For each field, the double-ended arrow indicates the difference between the measured net extraction of C from the atmosphere and the C that was harvested in the grain and hauled to market. If the NEE

Table 1
Carbon balance components for the conventional and alternative fields

Field treatment	CONV, conventional (full width tillage)	ALT, reduced tillage, spring oats before soybeans
Cumulative 2-year NEE	−376.1	−349.5
C removed in soybean harvest	150	141
C removed in maize harvest	317	295
Total C removed in harvests	467	436
NEE/harvested C	0.805	0.802
Apparent Δ soil C	−91	−86

All values are reported in $g\,C\,m^{-2}$.

data are accepted as accurate, this represents (see Eq. (2)) a net loss of SOC of 85–90 $g\,m^{-2}$ over the 2-year period. An alternative hypothesis is that this represents a systematic underestimate of NEE by eddy covariance. If this were true, the ratios of NEE to harvested C in Table 1 (0.809 and 0.805) would represent the 'carbon closure' of the eddy covariance measurements, analogous to the commonly reported energy balance closure.

This is not inconsistent with a substantial body of evidence indicating that eddy covariance systematically underestimates scalar fluxes. Kanda et al. (2004) have conducted large eddy simulations that indicate that even under 'best case' field conditions, with a uniform, level surface and no sensor errors, eddy covariance measurements from a single tower will systematically underestimate areally-averaged

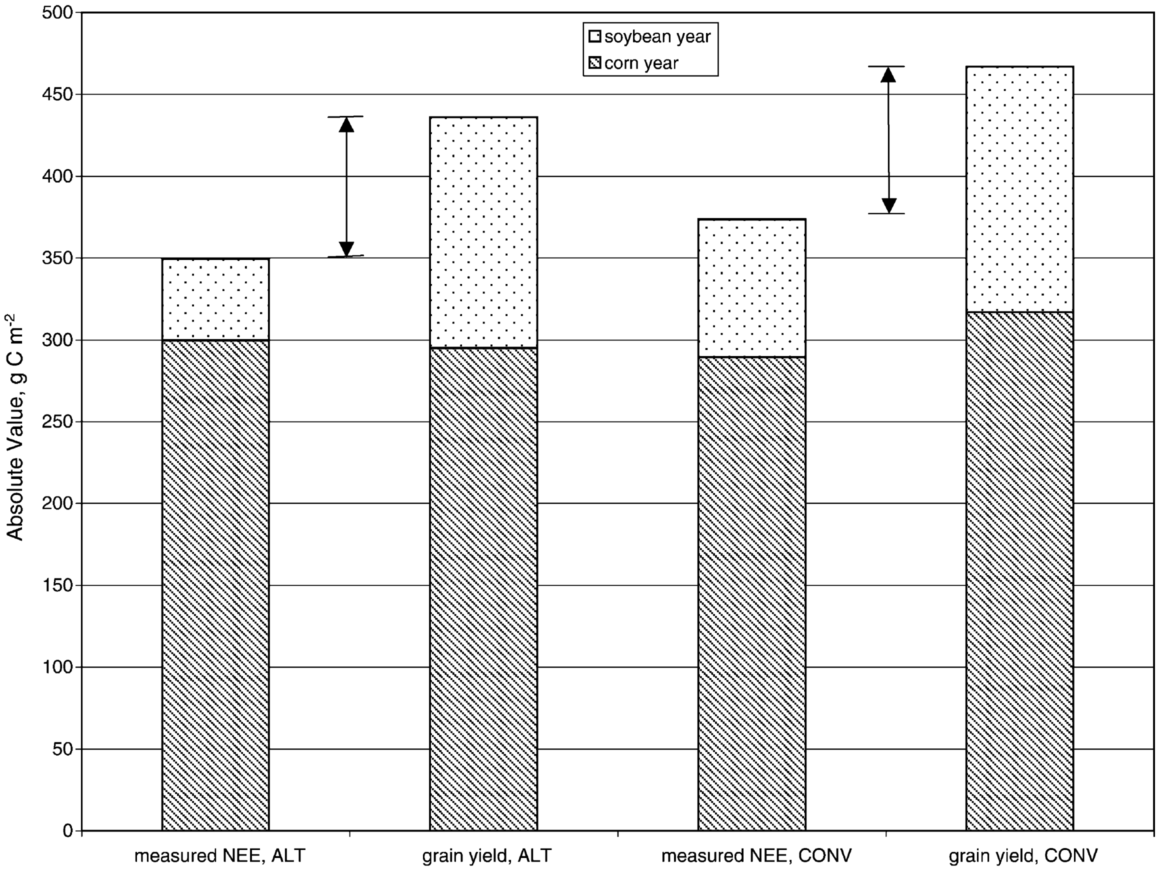

Fig. 5. Carbon balance components for each field for the 2-year period of the rotation. All values are expressed in $g\,C\,m^{-2}$.

fluxes due to local advection, caused by turbulent structures at long time scales.

Twine et al. (2000) conducted a comparison of eddy covariance measurements of latent and sensible heat against measurements of available energy (net radiation minus soil heat flux) and found that the summed eddy covariance measurements were consistently lower, by 10–30%. Wilson et al. (2002) examined data from FLUXNET sites throughout the United States and Europe and also found a consistent lack of energy balance closure that indicated a shortage in eddy covariance measurements of latent and sensible heat that averaged 20%.

We examined this issue in a cumulative sense by comparing the integrated measurements of latent heat flux over a 103-day period in summer 2003 in CONV with a water balance for the same period that was obtained by combining measured precipitation with the change in profile soil water content from the beginning to the end of the period. Equilibrium tension lysimeters (Masarik et al., 2004) confirmed that there was no drainage below the root zone during the period, simplifying the analysis. Cumulative eddy covariance measurements were 84.6% of the total water balance ET estimate (Table 2). This is remarkably consistent with the mean energy balance closure (slope 0.854) that we found when comparing summed latent and sensible heat against net radiation minus soil heat flux during the growing season. We cannot assume a priori that the factors causing underestimation of latent and sensible heat flux will affect CO_2 flux measurements to the same extent. Direct measurements of SOC are of no help in resolving this uncertainty. The hypothetical SOC change in each field over the 2-year period (85–90 g m^{-2}) would be distributed over a root zone that extends to at least 0.8 m depth, in a soil with a mean value of 2.3% SOC and a mean bulk density of 1.35 Mg m^{-3}, representing a background level of 25 kg C m^{-2}. In other words, it would require detection of a change in mean %SOC from 2.30 to 2.292%. The spatial variation of SOC is such that a prohibitively large number of samples would be necessary to resolve such changes at the farm field scale. Allmaras et al. (2004), in a long-term tillage experiment (13 year) with extensive soil sampling (8 samples/year on 75 m^2 treatment plots) of a similar soil within 1 km of our site, reported a standard error in ΔSOC of 120 g m^{-2}. There are geostatistical techniques that can be used to improve sampling strategies, but it is doubtful that there is any practical means by which we could distinguish the change in SOC of each of these systems over two years, much less the small difference between them (6 g m^{-2}) that is indicated by the eddy covariance and yield measurements.

Table 2
Water balance components for the conventional field for the 103-day period from DOY 172 to DOY 275, 2003

Component	Amount
Precipitation	229 mm
Change in soil moisture, surface to 1 m depth	90 mm
Drainage	0
ET, by water balance	319 mm
ET, by eddy covariance	270 mm
ET_{ec}/ET_{eb}	0.846

Soil water content was measured with an automated time domain reflectometry system, with waveguides at 8 depths, from 5 cm down to 1 m.

A cautious summation is that, for both systems, cumulative measured NEE over the two year corn soybean rotation was approximately 20% less than the total C removed from the field in grain harvests. If we accept the measurements as correct they indicate that both farming systems lost approximately 80–90 g m^{-2} during the 2-year period. This would represent an annualized loss of 0.4–0.45 mt ha^{-1}, comparable to loss rates reported in other annual cropping systems (McGinn and Akinremi, 2001; Robertson et al., 2000). However, concurrent eddy covariance measurements of latent heat flux appear to have underestimated water vapor loss by about 15%. If we accept similarity for both scalar measurements, it implies negligible change in SOC during the period. In any event, there was only a slight difference in estimated ΔSOC (6 g m^{-2}) between the two treatments, and that is the point of the paired flux approach. This difference is well below existing reports of the resolution of cumulative NEE measurements by eddy covariance (Goulden et al., 1996; Morgenstern et al., 2004). Thus, the data do not support the hypothesis that reduced tillage and a spring cover crop will measurably improve the C balance of a corn/soybean rotation, at least within the first 2 years of implementation. The optimistic estimates of SOC gain that have been made elsewhere have primarily been based on the more extreme contrast of full, continuous no-till agriculture versus moldboard plowing. Since much of the land that was historically moldboard plowed has already been converted to less aggressive forms of tillage, extrapolations of these estimates may be unwarranted.

A casual perusal of the data leads to the suggestion that a change to continuous corn might be a more productive means to sequester carbon, but that may not be the case. While corn clearly produces more biomass, our experience with the oats cover crop shows that additional biomass production does not necessarily translate to increased annual NEE or SOC. With respect to Eq. (2), perhaps a more fruitful sequestration approach is to focus less on ΔSOC and more on $Y[C_f]$, the harvested C. Historically most of the U.S. agricultural production has found its way to animal feed stocks or food production, so that the harvested C is rapidly respired back to the atmosphere. If the overall goal is simply to slow the increase in atmospheric CO_2, an increased focus on alternative products, either those with long lifetimes or those that substitute for fossil fuels, might be more effective than any policies that attempt to monetarily stimulate practices that are thought to increase SOC. However, when one also considers the ancillary benefits of increased SOC, such as increased water holding capacity and increased cation exchange capacity, it makes good sense to encourage adoption of farming systems that do so, even if the capability to measure SOC changes with the resolution necessary to verify them remains elusive.

4. Conclusions

We have examined the impact of two management practices, strip tillage and cover cropping, on the NEE of a biennial corn/soybean rotation, the prevalent cropping system in the Midwestern United States. The effects of reduced tillage intensity are subtle, but appear to show lower microbial respiration during the interval between fall plowing and the onset of winter. With respect to a spring oats cover crop, the data indicate that the additional carbon fixed by the cover crop is lost via higher respiration during the summer after the crop has been sprayed with herbicide and replaced with soybeans. A fall-planted cover crop, such as winter wheat or rye, might be more effective, since the combined fall and spring growth should produce deeper rooting. An even more effective approach may be to employ cover crops, or even companion crops, that allocate more of their biomass to recalcitrant C compounds. The technique of paired-flux measurement offers promise for comparing the *relative* sequestration potential of competing management practices at adjacent sites, but in the end, absolute measurements are necessary to determine the bottom line of net C balance, and they must be both continuous and accurate to determine the often small difference between the annual grand inhalation and exhalation of CO_2 in terrestrial ecosystems.

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