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Net carbon flux from agriculture: Carbon emissions, carbon sequestration, crop yield, and land-use change

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Abstract. There is a potential to sequester carbon in soil by changing agricultural management practices. These changes in agricultural management can also result in changes in fossil-fuel use, agricultural inputs, and the carbon emissions associated with fossil fuels and other inputs. Management practices that alter crop yields and land productivity can affect the amount of land used for crop production with further significant implications for both emissions and sequestration potential. Data from a 20-year agricultural experiment were used to analyze carbon sequestration, carbon emissions, crop yield, and land-use change and to estimate the impact that carbon sequestration strategies might have on the net flux of carbon to the atmosphere. Results indicate that if changes in management result in decreased crop yields, the net carbon flux can be greater under the new system, assuming that crop demand remains the same and additional lands are brought into production. Conversely, if increasing crop yields lead to land abandonment, the overall carbon savings from changes in management will be greater than when soil carbon sequestration alone is considered.

Introduction

Transferring carbon from the atmosphere to terrestrial ecosystems could offset some of the carbon dioxide (CO_2) emissions from fossil-fuel burning. In agricultural lands, techniques such as decreased tillage and efficient use of fertilizers and irrigation have been proposed as ways to increase soil organic carbon (SOC) and decrease atmospheric CO_2 (Lal et al. 1998 IPCC 2000). However, much emphasis has been placed on carbon sequestered in the soil, and not on the actual impact that carbon sequestration activities might have on the atmospheric CO_2 pool. The use of a full carbon cycle analysis, as used by Schlamadinger and Marland (1996) for forest ecosystems, is demonstrated here using data for an agricultural ecosystem. The analysis accounts for both carbon sequestered and CO_2 emitted as a result of specific management practices. We extend the analysis to include CO_2 emissions from fossil-fuel use and changes in SOC associated with changes in land use that might arise if carbon sequestration activities result in changes in crop yield (Figure 1).

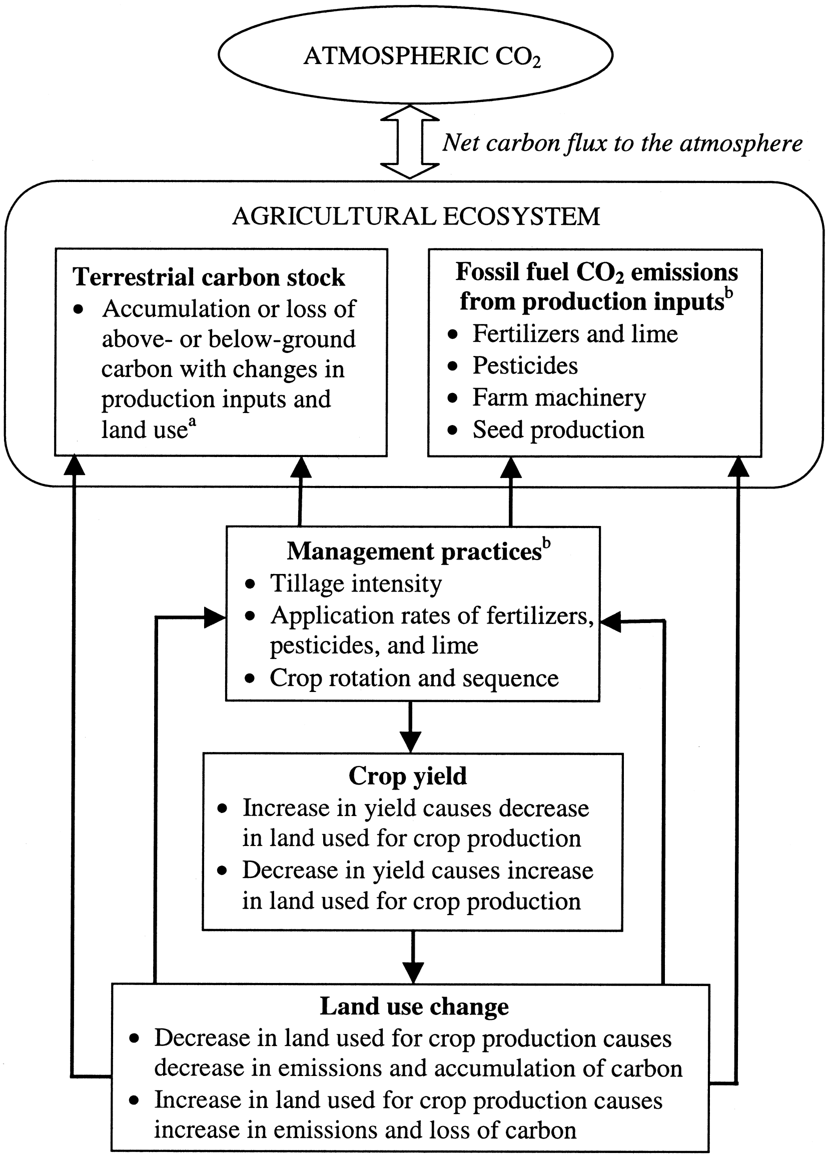

Figure 1. Schematic of factors that affect net carbon flux to the atmosphere as a function of agricultural practice. [a] Changes in aboveground carbon that may be associated with changing land use on forested lands are not included in this analysis. [b] Although irrigation water is not included in this analysis, irrigation can also contribute to carbon emissions and changes in soil organic carbon (West and Marland 2002a (in press)).

This analysis relies on data from a 20-year agricultural experiment (Frye and Blevins 1997 Ismail et al. 1994 Blevins et al. 1983) in Kentucky, USA, that involved corn (*Zea Mays* L.) grown with a winter cover crop of rye (*Secale cereale*

L.). The experiment used four different nitrogen (N) application rates across two tillage practices. Conventional tillage (CT) included the use of a moldboard plow and chisel, while the no-till (NT) method did not till, cultivate, or otherwise disturb the soil profile. The experimental site had been a bluegrass pasture for approximately 50 years prior to the experiment. For a more detailed explanation of the materials and methods used in the Kentucky experiment see Frye and Blevins (1997) and Ismail et al. (1994). This analysis is confined to carbon dynamics and does not consider any effects on other greenhouse gases, such as methane and nitrous oxide.

Carbon dioxide emissions

Estimates of CO_2 emissions associated with different combinations of CT, NT, and N fertilizer application rates in the Kentucky experiment (Table 1) were calculated using carbon emission coefficients for inputs to agricultural production (West and Marland 2002a (in press)). While many of the inputs to production in this experiment were representative of common cropping practices, the application rate of potassium (K) was uniform across all plots and slightly higher than average application rates. This was done in order to rule out K as a limiting factor of crop yield in the experiment (W.W. Frye, personal communication 2000). Phosphorus (P) was applied to all plots in the first year but was not applied again as the plots had naturally high P levels. The experiment used herbicide application rates that were constant across all trials and very close to the average for no-till corn systems in the US. No pesticide applications were reported.

Carbon sequestration and net carbon flux

Carbon sequestered in soil over the 20-year period was measured for each combination of fertilizer rate and tillage type. We calculated carbon sequestration relative to the change in SOC in the uncultivated control plots (Table 2). Schlesinger (1999) used the conventional tillage plots with no N fertilizer as his reference for estimates of carbon sequestration over the same experiment. While the two approaches lead to different estimates for carbon sequestered, they result in the same numbers for the relative net carbon flux, as shown in Table 2.

Relative net carbon flux is defined as the difference between the net carbon flux associated with a given management practice and that associated with the original or baseline management practice (West and Marland 2002b). The value for relative net carbon flux is intended to represent the overall impact on atmospheric CO_2 from changing management practices to sequester carbon. Our estimates of relative net carbon flux to the atmosphere are relative to the experimental trial using CT and 168 kg N ha^{-1} yr^{-1}, because this trial condition most closely represents prevailing

Table 1. Carbon dioxide emissions from inputs to production for a continuous corn crop in Kentucky.[a]

	Conventional Till				No-till			
N applied (kg N ha^{-1} yr^{-1}):	0	84	168	336	0	84	168	336
Production inputs	Carbon flux to the atmosphere (kg C ha^{-1} yr^{-1})							
Plow	26.75	26.75	26.75	26.75	0.00	0.00	0.00	0.00
Disk (twice)	17.44	17.44	17.44	17.44	0.00	0.00	0.00	0.00
Planting (corn)	6.79	6.79	6.79	6.79	6.79	6.79	6.79	6.79
Seed (corn)[b]	22.26	22.26	22.26	22.26	22.26	22.26	22.26	22.26
Harvest (corn)	16.47	16.47	16.47	16.47	16.47	16.47	16.47	16.47
Broadcast planting (rye)[c]	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46
Seed (rye)[d]	33.09	33.09	33.09	33.09	33.09	33.09	33.09	33.09
Herbicide application	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Herbicide[e]	17.12	17.12	17.12	17.12	17.12	17.12	17.12	17.12
Fertilizer application	8.03[i]	12.35	12.35	12.35	8.03[i]	12.35	12.35	12.35
Nitrogen (N)	0.00	72.03	144.07	288.13	0.00	72.03	144.07	288.13
Potassium (K)[f]	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
Lime application[g]	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Lime[h]	45.65	45.65	45.65	45.65	45.65	45.65	45.65	45.65
Total CO_2 emissions	209.45	285.80	357.84	501.90	165.26	241.61	313.65	457.71

[a] Based on agricultural inputs detailed by Frye and Blevins (1997) and Ismail et al. (1994), Blevins et al. (1983). Fields were not cultivated after planting and there are no data for application of pesticides or fungicides. Soils were naturally high in P and we do not show emissions for the one, initial year of P application. Conversion of agricultural inputs to CO_2 emissions is based on data circa 1995 (West and Marland 2002a (in press)).

[b] Application rate of corn seed was estimated to be 21 kg ha^{-1} yr^{-1}, based on establishment of 50,000 plants ha^{-1}, 95% germination, 5% mortality, and a 1,000 kernel weight of 380 g (Miller and McLelland 2000).

[c] Rye was planted as a winter cover crop. Broadcast planting for the rye cover crop assumes 1.4 L ha^{-1} (72 MJ ha^{-1}) of diesel (Bowers 1992) and 42 MJ ha^{-1} embodied in the manufacture, transport, and repair of machinery (West and Marland 2002a (in press)).

[d] Application rate of rye seed was 188 kg ha^{-1} yr^{-1}. Cost of rye seed was assumed to be \$0.42 kg $^{-1}$ (Windham 1999).

[e] Average application rate of 3.64 kg ha^{-1} yr^{-1} consists of 0.28 and 3.36 kg ha^{-1} yr^{-1} of paraquot and simazine, respectively.

[f] Average application rate of 62 kg K ha^{-1} yr^{-1} consists of 42 kg K ha^{-1} yr^{-1} in 1970 and 100 kg K ha^{-1} yr^{-1} from 1978–1989. A high K application rate was used to minimize the effects of K as a confounding variable in the experiment.

[g] Carbon emissions from lime application were normalized by the number of years that lime was applied (3 out of 20 years; (West and Marland 2002a (in press)) and (W.W. Frye, personal communication 2000)).

[h] Lime was applied at a rate of 6.7 and 11.2 Mg ha in 1973 and 1975, respectively, and an estimated 9 Mg ha^{-1} in 1983. Lime is assumed to be 95% $CaCO_3$.

[i] For the plots where nitrogen was not applied, carbon emissions from fertilizer application were normalized by the number of years that K was applied (13 out of 20 years; West and Marland (2002a) (in press) and W.W. Frye (personal communication 2000)).

Table 2. Net C flux to the atmosphere as a function of tillage practice, N fertilizer application, and crop yield.[a]

	Conventional Till				No-till			
N applied (kg N ha^{-1} yr^{-1}):	0	84	168	336	0	84	168	336
	Carbon flux to the atmosphere (kg C ha^{-1} yr^{-1})							
A. Assuming that the area in crop production does not vary with yield.								
CO_2 emissions[c]	+209	+286	+358	+502	+165	+242	+314	+458
C sequestration[d]	+303	−70	−75	−323	−25	−173	−200	−568
Net C flux	+512	+216	+283	+179	+140	+69	+114	−110
Relative net C flux[e]	+229	−67	0	−104	−143	−214	−169	−393
B. Assuming that changes in corn yield are 20% compensated by changes in the area in corn production.[b]								
Adjustment in emissions due to land use change[f]	+21	+3	0	−3	+22	+2	−3	−6
Adjustment in sequestration due to land use change[g]	+73	+7	0	−2	+99	+8	−3	−4
Adjusted relative net C flux[h]	+323	−57	0	−109	−22	−204	−175	−403
C. Assuming that changes in corn yield are 100% compensated by changes in the area in corn production to maintain constant total corn production.[b]								
Adjustment in emissions due to land use change[f]	+103	+13	0	−14	+109	+12	−16	−28
Adjustment in sequestration due to land use change[g]	+367	+33	0	−10	+493	+38	−17	−21
Adjusted relative net C flux[h]	+699	−21	0	−128	+459	−164	−202	−442

[a] Negative values represent net withdrawal of CO_2 from the atmosphere; positive values represent net emissions of CO_2 to the atmosphere. Estimates of C sequestration, net C flux, and respective adjusted values are for initial years following changes in management and land use.

[b] Measures of C emissions and sequestration are per original hectare, i.e. if additional area has to be cleared and planted in order to maintain total corn production, any CO_2 emissions from this land conversion and use are counted on the original one hectare.

[c] From Table 1.

[d] Annual C sequestration over the duration of the experiment, relative to uncultivated plots, using data from Ismail et al. (1994).

[e] Net carbon flux relative to a baseline. The baseline value (+283 kg C ha^{-1} yr^{-1}) is for conventional tillage with 168 kg N ha^{-1} yr^{-1}, which roughly represents current conventional practice in the US

[f] Changes in yield result in a change in the amount of land in production, if total production is to be maintained. Farming more or less land will change the amount of agricultural inputs required and the amount of fossil fuel consumed.

[g] Changes in yield result in a change in the amount of land in production, if total production is to be maintained. This will require bringing additional land into production or permit abandonment of land currently in production. Numbers here are for loss or gain of soil organic carbon (SOC) and do not consider clearing or planting of forest which might involve large quantities of above-ground carbon.

[h] Relative net carbon flux including adjustments in CO_2 emissions and SOC as a result of changes in the amount of land in production. Adjustments in emissions and SOC are relative to the yield obtained from using conventional tillage with 168 kg N ha^{-1} yr^{-1}.

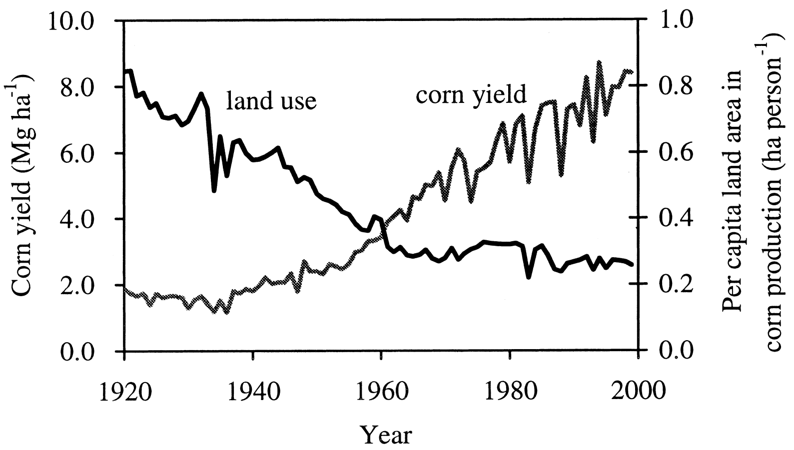

Figure 2. Comparison of average corn yield and land area in corn production in the US (USDA 2000a US Census Bureau 2000). (1 bushel corn per acre = 0.0628 Mg ha^{-1})

agricultural practice (i.e. CT using approximately 140 kg N ha^{-1} yr^{-1} (USDA 2000a)).

Effect of changes in yield on net carbon flux

Yield as a factor of land-use change

Activities used to sequester carbon in cropland soils have the potential to alter land use and land cover indirectly through their effect on crop yields. For example, if yields increased while crop demand remained unchanged, land used for cultivating the crop would be expected to decrease. Conversely, if crop yield decreased, it is expected that additional lands would be cultivated somewhere to meet demand. This expected trend is illustrated by a comparison between average corn yield and the amount of land, per capita, used to produce corn for the past 80 years in the US (Figure 2). The trend is also observed globally, where it has been estimated that the "land spared since 1960 by raising yields of grain...equals the [area of the] Amazon basin (Ausubel 1996)."

While the global crop yield per hectare has risen 2.15 percent annually between 1960 and 1994, the total area of cropland has remained stable since the mid 1900s (Ausubel 1996). Waggoner (1997) showed that grain used in the US for animal feed and for export remained relatively constant over this time and that the increase in yield compensated for the increase in population, resulting in relatively little change in land use. Consequently, Figure 2 shows land use per capita, and our estimates of land-use change hereinafter presume constant population.

In our analysis, when yield decreased it was assumed that additional land might be brought into production to compensate for the lost yield (and vice versa for an increase in yield). We used three different scenarios of yield versus land-use change to illustrate the importance of considering the effect of agricultural management on yield, with respect to carbon sequestration initiatives. Scenario A assumes that a change in yield results in no change in land use. Scenario B is used to represent the observed US trend in yield vs. land use since 1960 (Figure 2), e.g., that for every one percent change in corn yield, there is a negative 0.2 percent change in land used for corn production. Scenario C assumes that, with the demand for corn remaining the same, for every decrease in yield the necessary amount of land is brought into production to completely replace the lost yield.

Carbon dynamics associated with land-use change

Our calculations include the CO_2 emissions associated with crop production on any additional land brought into production, as well as emissions from the change in land use. Changing from non-cropland (i.e. grassland or forest) to cropland was assumed to release 750 kg C ha^{-1} yr^{-1} for the initial 20 years following conversion (Mann 1986). This represents carbon losses from grassland or forest soils. We make no assumptions about carbon losses from the above-ground vegetation, and carbon releases to the atmosphere would be very much larger if forest was cleared in order to cultivate land. Following an increase in yield, we assume that lands would be taken out of production, CO_2 emissions associated with crop production on those lands would cease, and the previously cropped land would become either grassland or forest with an accompanying soil carbon sequestration rate assumed to be 335 kg C ha^{-1} yr^{-1} (Post and Kwon 2000). Again, we make no assumptions about carbon that might be sequestered in above-ground vegetation if the abandoned land was converted to forest. Rates of soil carbon accumulation or loss are expected to approach zero over time as the soil reaches a new equilibrium following the change in management or land use (West and Marland 2002a (in press)). In this study, we only consider changes in the carbon budget during the initial years following changes in management and land use, hence changes in sequestration or loss rates over time are not represented.

The denominator in all of our calculations is “original hectares”, i.e. the amount of land cultivated in the baseline case. As an example, if yield is halved, scenario C would envision a doubling of the land in corn, but the per hectare carbon balance would still be in terms of the original number of hectares in corn. This provides a useful perspective in terms of the impact of changing agricultural practice in order to increase carbon sequestration on current cultivated areas. An alternative would be to estimate carbon sequestration per ton of grain, but our tendency is to think of carbon balances in terms of area in cultivation.

Net carbon flux: a comprehensive analysis

If we look at data from the Kentucky experiment and do not consider changes in corn yield, i.e. consider only carbon sequestration and the CO_2 emissions associated with inputs to production (Scenario A), the net carbon flux to the atmosphere was smallest for the no-till system using the highest level of fertilizer application (Table 2). Expressed relative to the system using CT with 168 kg N ha^{-1} yr^{-1} (our baseline system), the system with NT and 336 kg N ha^{-1} yr^{-1} reduced atmospheric CO_2 the greatest, with a relative net carbon flux of −393 kg C ha^{-1} yr^{-1}. Note that the absolute net carbon flux to the atmosphere from the NT system using 168 kg N ha^{-1} yr^{-1} was positive (+114 kg C ha^{-1} yr^{-1}), i.e. it was a net contributor to the atmospheric CO_2 pool. However, compared to the CT baseline with 168 kg N ha^{-1} yr^{-1}, changing to the no-till system reduced the net atmospheric CO_2 flux by 169 kg C ha^{-1} yr^{-1}.

Average annual corn yield for this 20-year Kentucky experiment ranged from 4.29 Mg corn ha^{-1} (for NT and 0 kg N ha^{-1} yr^{-1}) to 7.58 Mg corn ha^{-1} (for NT and 336 kg N ha^{-1} yr^{-1}). The baseline experiment (CT and 168 kg N ha^{-1} yr^{-1}) produced an average corn yield of 7.11 Mg corn ha^{-1}. Yields decreased dramatically as fertilizer rates decreased to 0 kg N ha^{-1} yr^{-1}. Although yields for all combinations of tillage and fertilizer application decreased with time over this 20-year experiment, we use the 20-year mean in our calculations. If we consider the impact of decreases in yield at low fertilization levels, assuming constant demand for corn, a large carbon flux to the atmosphere would occur due to carbon emissions associated with new land being brought into production. For example, the no-till system using no N fertilizer resulted in net carbon savings of 143 kg C ha^{-1} yr^{-1}, relative to the established baseline system, and when changes in yield and land use were not considered. When using scenario C, i.e. assuming that there is no change in demand for corn and that the loss in yield will be compensated by an increase in cropland area, the same system becomes a net contributor of 459 kg C ha^{-1} yr^{-1} to the atmosphere (see Table 2).

Plotting the values for relative net carbon flux for both tillage practices, over a gradient of N application rates, allows for an approximation of the optimum level of N fertilizer that results in the minimum net carbon flux (Figure 3). Results from the Kentucky experiment suggest that increasing the N fertilizer application rate generally decreases the net flux of carbon to the atmosphere, because the energy cost of additional fertilizer is more than compensated by the increases in carbon sequestration and corn yield. The increase in soil carbon accumulation associated with higher rates of N application is probably caused by a decline in microbial activity and, hence, the decreased decomposition of soil organic matter that occurs when soil pH decreases as a result of high N application (Blevins et al. 1983 Ladd et al. 1994 Söderström et al. 1983).

We note that the slope of the lines in Figure 3 is very much greater at low levels of N application. Increasing crop yield frees land for carbon sequestration but carbon uptake occurs at more modest rates than the loss of carbon that accompanies

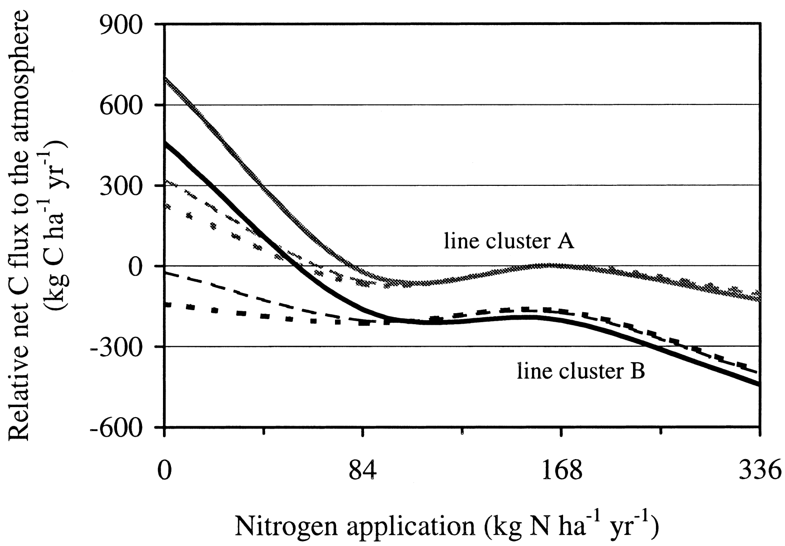

Figure 3. Relative net C flux representing two tillage practices and three scenarios of how land-use change might be affected by changes in corn yield. Relative net C fluxes assume that (broad-dashed line) crop area does not vary with yield, (narrow-dashed line) changes in corn yield are 20% compensated by changes in the area in corn production, and (solid line) changes in corn yield are 100% compensated by changes in the area in corn production to maintain constant total corn production. Response curves of relative net C flux represent (line cluster A) a continuation of conventional tillage practices and (line cluster B) changing from conventional tillage to no-till. All relative net C flux estimates are relative to a baseline value (conventional tillage with 168 kg N ha^{-1}). Based on values from Table 2.

bringing more land into cultivation. Again, the slopes of both sets of lines would be greater if we included changes in above-ground carbon stocks.

Other environmental effects caused by relatively high application rates of N fertilizer (including increased N_2O emissions, potential leaching of N into groundwater, and soil acidification) need to be examined more closely before recommending increased fertilizer use as a carbon sequestration strategy. For example, considering the relative importance of N_2O emissions in analyses of CO_2-equivalent flux to the atmosphere (Robertson et al. 2000) and that N_2O has approximately 310 times the radiative forcing of CO_2 (Houghton et al. 1996), an increase in the production of N_2O at high N application rates (Mosier et al. 1998) could counterbalance the positive effect of N fertilizer on the carbon budget. Emissions of N_2O were not measured in the Kentucky experiment and our research here is restricted to an analysis of carbon dynamics.

Conclusions

The practices that sequester the most carbon are not necessarily the practices that reduce net emissions of CO_2 to the atmosphere the most. Carbon sequestration activities can lead to changes in fossil-fuel use and can cause changes in land use and land cover that further impact the atmospheric CO_2 pool. Carbon emissions attributed to changes in land use and land cover, as well as carbon emissions from fossil fuel combustion, can significantly impact the success of management strategies that are intended to enhance carbon sequestration and to decrease the atmospheric CO_2 concentration. In the case of agricultural ecosystems, if crop yields increase, then CO_2 mitigation may be greater than anticipated based on carbon sequestration alone. If yields decrease, emissions associated with the additional lands necessary to replace lost yields can offset the savings in emissions associated with decreased rates of fertilizer application or the increase in SOC that may have occurred from a change in agricultural practice.

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