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Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model

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"Capsule": *The DAYCENT model predicts dryland agricultural soils will be net sources of greenhouse gases but the magnitude can be reduced through management practices.*

Abstract

We present evidence to show that DAYCENT can reliably simulate soil C levels, crop yields, and annual trace gas fluxes for various soils. DAYCENT was applied to compare the net greenhouse gas fluxes for soils under different land uses. To calculate net greenhouse gas flux we accounted for changes in soil organic C, the C equivalents of N_2O emissions and CH_4 uptake, and the CO_2 costs of N fertilizer production. Model results and data show that dryland soils that are depleted of C due to conventional till winter wheat/fallow cropping can store C upon conversion to no till, by reducing the fallow period, or by reversion to native vegetation. However, model results suggest that dryland agricultural soils will still be net sources of greenhouse gases although the magnitude of the source can be significantly reduced and yields can be increased upon conversion to no till annual cropping. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: C sequestration; Greenhouse gases; Land use; Modeling; DAYCENT

1. Introduction

Sequestration of carbon (C) in soil organic matter (SOM) has been suggested as a means to compensate for greenhouse gas emissions (Bruce et al., 1999; Lal et al., 1998). Observations show that some agricultural practices (conventional tillage, summer fallow) can deplete soils of C (Higgins et al., 1998) and that C depleted soils can sequester C upon change of management (Halverson et al., 1999; Paustian et al., 1992). In addition to acting as a sink for atmospheric CO_2, increasing C in soil also increases soil fertility and water retention. However, the greenhouse gas benefits of increasing soil C are at least partially offset because agriculture tends to increase the net fluxes to the atmosphere of nitrous oxide (N_2O) and methane (CH_4). The atmospheric concentrations of N_2O and CH_4 are much lower than that of CO_2, but N_2O and CH_4 are important greenhouse gases because they make a larger contribution to the greenhouse gas effect than CO_2 on a per molecule basis.

CO_2 is released to the atmosphere during nitrogen (N) fertilizer production and N fertilizer application usually results in increased nitrous oxide emissions. CH_4 oxidation in non-saturated soils acts as a sink for atmospheric CH_4, but N fertilization and tillage tend to decrease CH_4 uptake in soils because the enzyme that oxidizes CH_4 also has an affinity for ammonium (Bronson and Mosier, 1994) and conventional tillage alters soil structure such that porosity decreases and CH_4 diffusion into the soil decreases (Del Grosso et al., 2000c). To fairly compare the implications of different land use practices the effects of factors such as fertilizer, organic matter, and lime additions should be included in net greenhouse gas flux accountings (Robertson et al., 2000; Schlesinger, 1999, 2000). In this paper we calculate a net annual greenhouse gas flux which accounts for changes in SOM C, the C costs of fertilizer production, the C equivalents of N_2O emissions, and the C equivalents of CH_4 uptake for different land management scenarios. Winter wheat/fallow cropping, annual cropping, and reversion to native range grass were selected for com-

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parisons because the winter wheat/fallow system is commonly used in the central and southern US Great Plains region and the alternative management practices have been shown to store C in soil (Peterson et al., 1998). In this paper we describe the DAYCENT ecosystem model, validate the ability of DAYCENT to simulate SOM, N_2O emissions, and CH_4 uptake, and apply DAYCENT to compare the net greenhouse gas flux associated with the different land management scenarios.

2. Materials and methods

2.1. DAYCENT model description

The DAYCENT ecosystem model (Parton et al., 1998; Kelly et al., 2000; Del Grosso et al., 2001) simulates exchanges of C, nutrients (N, P, S), and gases (CO_2, CH_4, N_2O, NO_x, N_2) among the atmosphere, soil, and plants. Required inputs used to drive the model include daily maximum/minimum temperature and precipitation data, site specific soil properties, and current and historical land use. Disturbances and management practices such as fire, grazing, cultivation, and organic matter or fertilizer additions can be simulated. The submodels used in DAYCENT are described in detail by Del Grosso et al. (2001) and the model code is available from the authors. DAYCENT includes submodels for plant productivity, decomposition of dead plant material and SOM, soil water and temperature dynamics, and trace gas fluxes. Flows of C and nutrients are controlled by the amount of C in the various pools (e.g. SOM, plant biomass), the N and lignin concentrations of the pools, abiotic temperature/soil water factors, and soil physical properties related to texture. SOM is divided into three pools based on decomposition rates (Parton et al., 1993, 1994). Decomposition of SOM and external nutrient additions supply the nutrient pool that is available for plant growth and microbial processes that result in trace gas fluxes. Plant growth is controlled by a plant-specific maximum growth parameter, nutrient availability, and 0–1 multipliers that reflect shading, water, and temperature stress. Net Primary Productivity (NPP) is allocated among leafy, woody, and root compartments as a function of plant type, season, soil water content, and nutrient availability (Metherell et al., 1993). The land surface submodel of DAYCENT simulates water flow and evapotranspiration for the plant canopy, litter and soil profile, as well as soil temperature throughout the profile (Parton et al., 1998; Eitzinger et al., 2000).

The trace gas submodel of DAYCENT simulates N_2O, NO_x, and N_2 emissions from soils resulting from nitrification and denitrification as well as CH_4 oxidation in soils. The nitrification submodel simulates N_2O and NO_x emissions as a function of soil NH_4^+, water content, temperature, pH, and texture (Parton et al., in press). Nitrification is limited by moisture stress when soil water-filled pore space (WFPS) is too low and by O_2 availability when WFPS is too high. Optimum WFPS for nitrification is ~55%, with a higher optimum for clay than sandy soils. The denitrification submodel simulates N_2O, N_2, and NO_x emissions as a function of soil NO_3^-, water content, labile C availability (most denitrifiers are heterotrophs), and soil physical properties related to texture that influence gas diffusion rates (Del Grosso et al., 2000b). Denitrification, an anaerobic process, does not occur until WFPS exceeds 50–60% then it increases exponentially as WFPS increases and levels off as soils approach saturation. Simulated heterotrophic respiration rates are used as a proxy for labile C availability. NO_x emissions are calculated using total N_2O emissions, a NO_x:N_2O function based on soil gas diffusivity, and a pulse multiplier based on rainfall frequency and amount (Parton et al., in press). As soil gas diffusivity decreases, a smaller proportion of total N gas fluxes are assumed to be in the form of NO_x because NO_x becomes more reactive as soils become more reducing. The pulse multiplier equations were developed by Yienger and Levy (1995) and account for the observed high NO_x emission rates following precipitation events onto soils that were previously dry (Smart et al., 1999; Martin et al., 1998; Hutchinson et al., 1993). CH_4 uptake is controlled by soil gas diffusivity, water content, and temperature (Del Grosso et al., 2000c). CH_4 oxidation rates are assumed to be limited by gas diffusivity when θ (volumetric soil water content) is too high and by moisture stress on biological activity when θ is too low. Optimum θ values range from 0.06–0.22 cm^3 H_2O cm^{-3} soil. As with nitrification, clay soils are assumed to have a higher optimum water content for CH_4 oxidation than sandy soils.

2.2. DAYCENT validation

We summarize previous validations of DAYCENT then present results of model tests performed recently. The SOM and N cycling submodels used in DAYCENT have yielded favorable results when compared with data from various systems including agricultural soils in Sweden (Paustian et al., 1992) and Oregon (Parton and Rasmussen, 1994). DAYCENT has been shown to reliably model soil water content, N mineralization, and NPP for a shortgrass steppe in Colorado (Kelly et al., 2000). Simulated values of N_2O emission rates and CH_4 uptake rates agree reasonably well with observed data from different soil types and management practices (Parton et al., in press; Del Grosso et al., 2000c). Frolking et al. (1998) demonstrated the ability of DAYCENT to simulate soil water content, mineral N levels, and N_2O and CO_2 emissions for various systems including a native shortgrass steppe in Colorado, a ryegrass pasture in Scotland, and perennially cropped soils in Germany. Although DAYCENT did not always reliably simulate the observed daily patterns of N_2O emissions, it usually captured seasonal dynamics for particular sites accurately and correctly simulated the observed low annual emissions from native soils, the intermediate annual emissions associated with dryland cropping, and the high annual emissions from irrigated agricultural systems (Del Grosso et al., in press). DAYCENT has successfully simulated SOM levels in a US Great Plains soil used for winter wheat/fallow cropping and a Midwestern US soil used for corn/soybean/pasture rotations and has been used to compare the effects of alternative land management practices on soil C levels, greenhouse gas fluxes, and crop yields (Del Grosso et al., 2001).

To further test the ability of DAYCENT to simulate SOM and trace gas fluxes from soils under different management practices we compared results of model simulations with data from agricultural and native soils. Kessavalou et al. (1998a, 1998b) measured SOM, N_2O flux and CH_4 flux from soils used for winter wheat/fallow cropping under conventional and no till cultivation and soils with native grass cover. The data were collected at the High Plains Agricultural Research Laboratory at Sidney, Nebraska and the model was driven with a local daily weather file (annual ppt. ~147 cm, annual temperature ~19.6°C). Soil physical properties were parameterized using bulk density and texture data reported by Kessavalou et al. (1998a). The model was run for 70 years with native range grass to initialize the SOM and nutrient pools. Starting in 1970, DAYCENT files for cultivation and plant type were altered to reflect the land management practices that were implemented at that time. Plots were established in 1970 to measure the response of ecosystem parameters under conventional till winter wheat/fallow and no till winter wheat/fallow, while some plots were left in the native condition as controls (Kessavalou et al., 1998b). SOM values were measured in 1992 (Kessavalou et al., 1998b) and gas flux data were collected from 1993–1995 (Kessavalou et al., 1998a). No fertilizer was used for the winter wheat cropping.

The observed data showed highest SOM in the native grass soil and the lowest in the conventionally tilled winter wheat/fallow soil. The model showed the correct trends, but SOM was slightly overestimated for the native grass soil (Fig. 1a). The data and model both showed highest N_2O emission rates for the conventionally tilled crop soil and lower emissions for the no till cropped soil and native grass, although the model slightly underestimated emissions from the grass (Fig. 1b). CH_4 uptake was higher in the native soil and essentially equivalent in the cropped soils under the tillage alternatives considered for the model and data (Fig. 1c). Although the model correctly simulated average trace gas emission rates for the different soils very well (Fig. 1b, c), model performance on the daily time scale for particular soils was not as favorable. To demonstrate the variability in daily trace gas flux rates, Fig. 2 shows the simulated and observed trace gas flux values for the conventional till winter wheat/fallow soil for the time series considered. The model correctly simulated some of the observed high N_2O flux events but many events were mis-timed by the model (Fig. 2a). The r^2 value for observed versus simulated daily trace gas flux was higher for CH_4 (17%) than N_2O (4%) but there was still much variability in the data that was not accounted for by the model (Fig. 2b).

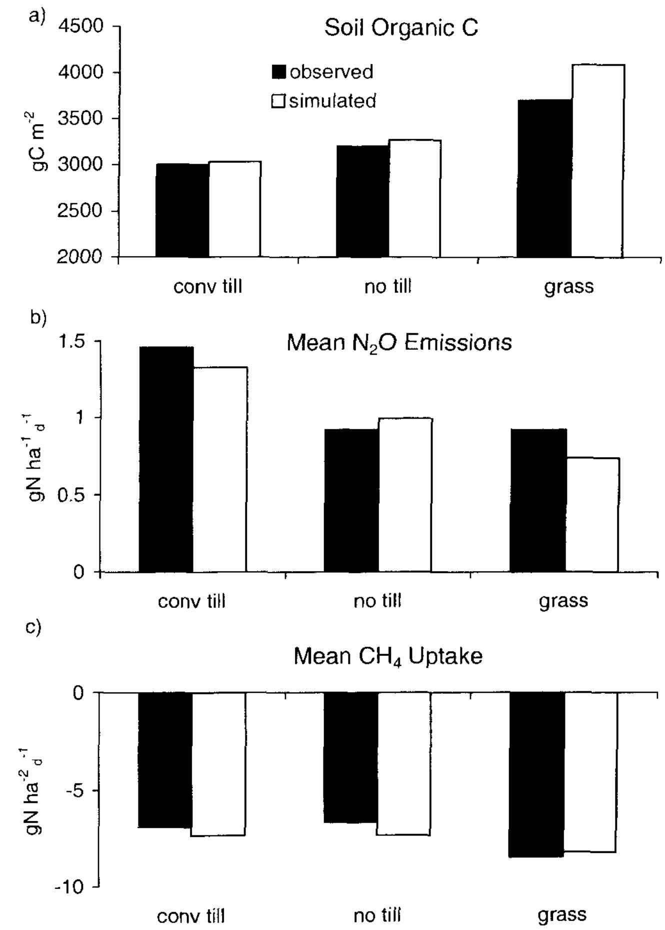

Fig. 1. DAYCENT simulated and observed values of (a) SOM C, (b) mean daily N_2O emissions and (c) mean daily CH_4 uptake rates for conventional till and no till winter wheat/fallow cropping and native range grass for data collected near Sidney Nebraska (Kessavalou et al., 1998a, 1998b). Positive values represent emissions from the soil to the atmosphere while negative values represent uptake of atmospheric gas by the soil.

A major source of model error is an inability to model soil WFPS correctly during the winter. WFPS is a major driver of the processes that lead to trace gas exchanges in soil (see DAYCENT model description section). Parton et al. (in press) showed that DAYCENT simulated WFPS better during May–October ($r^2 = 0.66$) than during November–April ($r^2 = 0.28$) for the aggregated data from different rangeland soils collected over an

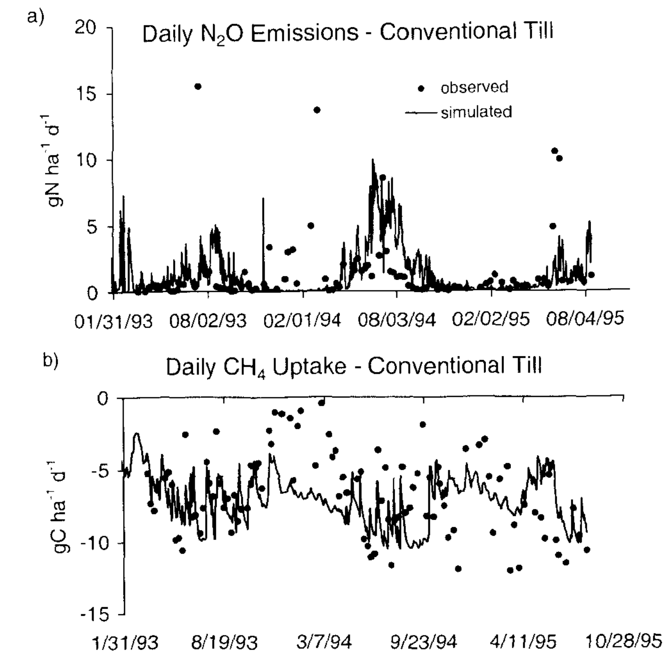

Fig. 2. Time series of simulated and observed daily (a) N_2O emission rates and (b) CH_4 uptake rates for the conventional till winter wheat/fallow soil near Sidney, Nebraska (Kessavalou et al., 1998b).

8-year period. We believe that the primary cause for model error during the winter season is spatial heterogeneity in snow accumulation, drifting, and melting due to topography and aspect, which are not accounted for by the model. Visual observations by the authors of variability in snow cover on experimental plots support this speculation. Overall, these results are consistent with earlier tests of DAYCENT which showed that the model usually simulated annual trace gas flux rates reasonably well (within 25% of observed values) even though daily variability was often not well represented (Del Grosso et al., in press; Parton et al., in press).

2.3. *DAYCENT application*

DAYCENT was applied to address the effects of different land management scenarios on net greenhouse gas fluxes between the atmosphere and the soil. Simulations were performed for dryland soils that were C depleted due to 50 years or more of conventional winter wheat/fallow cropping. The wheat/fallow cropping system has been used extensively in the southern and central Great Plains because this region is semi-arid and droughts are not uncommon. Traditionally, winter wheat was planted in September, harvested the following July, then the field was left fallow until September of the following year when winter wheat was again planted. The advantage of the crop/fallow system is that water stored during the fallow season increases the chances for seedling establishment when the crop is sown. The disadvantage of this system is that SOM is reduced by ~50% after 30–50 years of cropping (Peterson et al., 1998). Reasons for the decline in SOM include: during the fallow season carbon inputs to the soil are minimal but decomposition of SOM continues, ground cover during the fallow season is minimal so the soil is subject to wind and water erosion, and fields were regularly plowed during the fallow season to control weeds, which tends to increase SOM decomposition rates (Peterson et al. 1998). DAYCENT was used to simulate N_2O emissions, CH_4 uptake and changes in SOM C for experimental plots described by Peterson at al. (2000).

2.4. *Site description*

In 1985, Peterson et al. (2000) set up experimental plots at three sites in Colorado in fields that were previously used for conventional tillage winter wheat/fallow or sorghum cropping for ~50 years. The goals of the experiment were to study the effects of dryland cropping scenarios, landscape position, and potential evapotranspiration on soil C levels, economic value of crop yields, precipitation and N use efficiency, and other variables. Plots included winter wheat/fallow, annual cropping, and native range grass for each of three topographical positions (summit, sideslope and toeslope). The winter wheat/fallow plots are staggered in time such that the wheat crop and fallow period are both represented every year. Annual cropping involved growing a crop every year while avoiding monoculture. Crops used for the annual rotation included dryland corn, hay millet and winter wheat. Dryland corn was planted in May and harvested in October, hay millet was planted in June and harvested in August. Winter wheat was planted twice as part of the annual sequence because of summer crop failure due to moisture stress. No till cultivation was used exclusively for these agricultural plots. Fertilizer was added at the time of planting and the amounts, ranging from 2.2–11.3 g N m^{-2}, were based on measured soil NO_3^- concentration and expected crop yield. Grain was harvested for winter wheat and corn and the stover was left on the soil surface. The millet crop was harvested for hay. No fertilizer was added to the grass and it was not harvested or grazed. The crop yields reported in this paper were obtained by averaging the yields from each of the three slope positions for data collected from 1986–1998 at the Sterling, CO site.

2.5. *Simulations and results*

We first describe how the model simulations were conducted, then we establish that the model reliably simulated grain yields and SOM C by comparing simulated and observed values of these variables. Lastly, we use simulated values of N_2O emissions, CH_4 uptake, and changes in SOM C to calculate a net greenhouse gas flux for each management alternative considered.

A weather file obtained from a station near the Sterling plots was used to drive model simulations (annual ppt. ~42 cm, annual temperature ~8.8 °C). Soil physical properties were paramaterized based on bulk density and texture data reported by Farahani et al. (1998) and Peterson et al. (2000). To initialize the SOM and nutrient pools the model was run for 50 years assuming conventional tillage winter wheat/fallow cropping. Starting in 1985, the DAYCENT vegetation and cultivation files were adjusted to reflect the land uses represented by the plots that were established at that time. No model equations were adjusted and standard crop and grass files were used without adjusting any parameters, such as maximum plant growth rates. Simulated data for annual grain yields, SOM C, and N_2O and CH_4 fluxes were complied for 1986–1998. To calculate a net greenhouse gas flux for each land use practice considered, we calculated the C equivalents of the N_2O and CH_4 fluxes based on a 100 year time horizon by assuming that a N_2O molecule has 310 times the global warming potential of a CO_2 molecule and that a CH_4 molecule has 21 times the global warming potential of a CO_2 molecule (Prather et al., 1995). We also assumed that each gram of N fertilizer produced results in the emission of 0.8 g CO_2-C to the atmosphere during manufacture (Schlesinger, 1999).

Fig. 3a shows that the model correctly simulated the observed SOM C gradient with the winter wheat/fallow having the lowest SOM C, the native grass having intermediate SOM C, and the annual cropping having the highest, although SOM C was slightly underestimated for the annual cropping. Fig. 3b shows observed and simulated average grain or hay yields for the winter wheat fallow and the three crops that were used for annual cropping (winter wheat, dryland corn, and hay millet). The winter wheat/fallow grain yields include the standard deviation bars ($n = 12$). Standard deviations are not shown for the annual crops because the sample sizes were small ($n < 5$) for each crop. Comparisons of observed and simulated crop yields show that the model does very well (Fig. 3b). Winter wheat yielded similar amounts of grain when alternated with fallow or with annual summer crops (Fig. 3b). Corn grain yields were somewhat higher than winter wheat and millet yields were the highest because this crop was harvested for hay. DAYCENT simulated essentially equivalent N_2O emission rates for the winter wheat/fallow and annual cropping and significantly lower emissions for the native grass (Fig. 3c). Simulated CH_4 uptake rates did not strongly differ among treatments, although the native grass absorbed slightly more CH_4 than the cropped soils (Fig. 3c).

Fig. 4a, b show the components used in the net greenhouse gas flux calculation. We neglect the effects of erosion, leaching, and C deposition on soil C levels and assume that changes in soil C are driven by exchanges of C between the atmosphere and the soil. Annual average gains in SOM C and the average annual

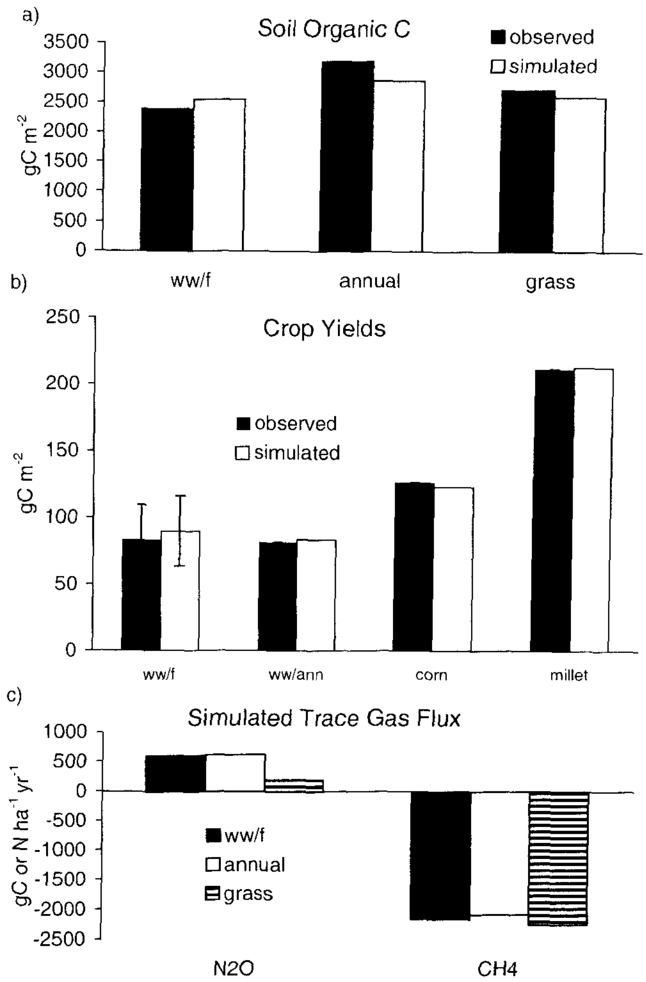

Fig. 3. (a) DAYCENT simulated and observed values for SOM C for no till winter wheat/fallow, no till annual cropping and native grass for data collected near Sterling, CO (Peterson et al., 2000). (b) DAYCENT simulated and observed crop yields for no till winter wheat/fallow, winter wheat as part of the annual cropping schedule, annual corn, and annual millet for data collected near Sterling. Error bars are shown for winter wheat/fallow ($n = 12$). (c) Simulated annual N_2O emission and CH_4 uptake rates for the Sterling plots.

C equivalents of CH_4 uptake are shown as negative values in Fig. 4a because both of these factors represent uptake of greenhouse gases by the soil. Annual cropping stored the most SOM while the winter wheat/fallow stored the least. Simulated CH_4 uptake did not significantly differ among the soils. Average annual C equivalents of N_2O emissions and the C equivalents associated with the manufacture of the N fertilizer applied to the respective land use alternatives are shown in Fig. 4b because both of these factors represent emissions of greenhouse gases to the atmosphere. Both of the cropped soils had essentially equivalent simulated N_2O emissions even though the annual cropping received more than twice the N fertilizer of the winter wheat/fallow system. Fig. 4c shows the net greenhouse gas flux for each soil calculated as the sum of the CO_2-C equivalents of the simulated change in SOM C, CH_4 uptake, N_2O emission, and CO_2 costs of N fertilizer production. Winter wheat/fallow was a net source of

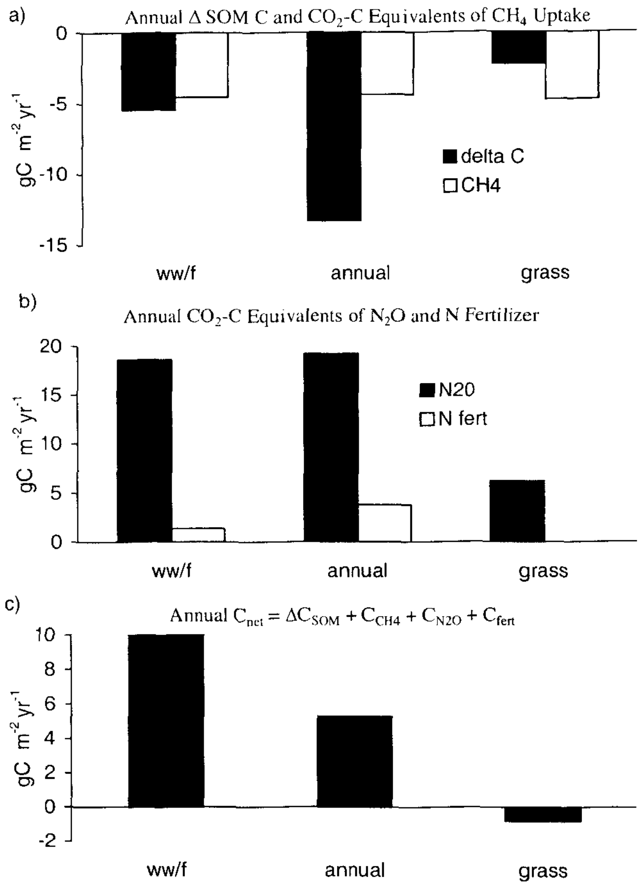

Fig. 4. (a) Annual uptake of CO_2-C driven by changes in SOM C (ΔC_{CO2}) and CO_2-C equivalents of CH_4 fluxes, (b) annual CO_2-C equivalents of N_2O emissions and CO_2-C emissions associated with N fertilizer production for simulations of no till winter wheat/fallow cropping, no till annul cropping, and native grass plots near Sterling, CO (Peterson et al., 2000) and (c) net annual greenhouse gas fluxes after accounting for the factors in (a) and (b). Positive values represent emissions from the soil to the atmosphere while negative values represent uptake of atmospheric gas by the soil.

greenhouse gases to the atmosphere, annual cropping was a somewhat smaller net source, and the native grass provided a net sink.

3. Discussion

Observations show that conventional tillage and fallow periods tend to decrease SOM C in agricultural soils and that C depleted soils can sequester C upon change of management (Higgins et al., 1998; Peterson et al. 1998; Paustian et al., 1997). However, the effects of management practices on fluxes of non-CO_2 greenhouse gases have not been as extensively measured. DAYCENT was used to simulate N_2O and CH_4 fluxes for plots designed by Peterson et al. (2000) to study the effects of cropping intensification on SOM C levels, crop yields and other ecological and economic factors. Both DAYCENT and observed SOM C values showed higher SOM C levels in native grass than winter wheat/fallow for two different soils (Figs. 1a and 3a) and DAYCENT showed an annual net accumulation of 2–13 g C m^{-2} $year^{-1}$ upon conversion from conventional tillage winter wheat/fallow to either native grass, no till winter wheat/fallow, or no till annual cropping (Fig. 4a). All of the land use alternatives in Fig. 4a accumulated C from CO_2 fixation because the soils were depleted from >50 years of conventional tillage winter wheat/fallow. The magnitude of C storage increased with NPP so that annual cropping showed the highest rate of C storage and native grass the lowest. The accumulation rates in Fig. 4a are for the first 12 years following conversion and C sequestration rates are expected to decrease as soils become C saturated (Paustian et al., 1998; Del Grosso et al., 2000a).

As was pointed out by Robertson et al. (2000), changes in SOM C are only part of the story and fluxes of non-CO_2 greenhouse gases must also be considered. As expected, native grass had the lowest simulated N_2O emissions, but N_2O emissions were essentially equivalent for the winter wheat/fallow and annual cropping even though the annual cropping received over twice the fertilizer inputs of the crop/fallow system (Fig. 4b). This can be explained by mineral N dynamics and by high simulated N_2O emissions during fallow summers. The annual cropping showed high rates of simulated N_2O emissions during the spring when fertilizer was applied but emissions were low during most of the growing season because the summer crops had high rates of N uptake so little N was available for nitrification and denitrification. Although the majority of simulated N_2O emissions occurred during the warmer months (May–September) both the annual and winter wheat/fallow soils showed significant denitrification N_2O fluxes during the winter in response to snow melting. The winter wheat showed lower simulated N_2O fluxes during the summer when compared to the annual cropping but higher winter time fluxes when winter wheat was sown in the fall. Fertilizer applied in September at planting maintained sufficient N levels to support relatively high N_2O emissions during the winters when winter wheat was present. The majority of simulated N_2O fluxes occurred during the fallow compared to the planted season (471 vs. 764 gN_2O-N ha^{-1} $year^{-1}$) for the winter wheat/fallow system. This may have been due to relatively high fluxes during the fallow summers when decomposition was mineralizing N but there was little competition for mineral N from plant uptake. The annual cropping was also storing SOM faster than the winter wheat/fallow cropping (Fig. 4a) so a smaller proportion of total soil N should have been available for the microbial processes that result in N_2O emissions.

Simulated CH_4 uptake rates were not significantly higher for the native grass compared to the cropped soils (Fig. 4a) because the native grass soil was used for winter wheat/fallow cropping for ~ 50 years and had been out of production for <15 years. There is evidence that agricultural soils which are converted back to native vegetation do not immediately consume CH_4 at rates of similar soils that have not been cropped for many years (Mosier et al., 1997; Robertson et al., 2000). The mechanisms that are responsible for the impact of disturbance on CH_4 uptake are not well understood so the effects of agriculture on CH_4 uptake are represented in a simple manner by the model. DAYCENT assumes that CH_4 uptake rates in soils that are currently cropped or were most recently cropped less than ~20 years ago will be depressed compared to similar native soils. In the long term, the reduced uptake of CH_4 associated with cropping is expected to be significant compared to the uptake of systems with native cover (Ojima et al., 1993).

DAYCENT simulations suggest that although cropping intensification and no till cultivation lead to sequestration of SOM C, some agricultural systems will still be net sources of greenhouse gases (Fig. 4c). Although native ungrazed grass sequestered C at a low rate, it was the only land use considered that showed net greenhouse gas uptake because it had low N_2O emissions and no CO_2 costs of N fertilizer production (Fig. 4). These results are consistent with observations of Robertson et al. (2000) that annual crops are net sources of greenhouse gases after accounting for changes in soil C, N_2O emissions and CH_4 uptake but that perennial crops and successional communities could be net sinks. We expect that simulations of native grass with grazing would store less C than grass without grazing because more C is respired as CO_2 and less enters the soil with grazing. Also, CH_4 emissions from enteric fermentation associated with grazing are expected to result in decreased net CH_4 uptake compared to ungrazed native dryland systems. However, compared with high intensity agriculture, grazing would likely provide benefits from a net greenhouse gas perspective, particularly if the CO_2 costs of plowing, harvesting, and transporting feed grain were included.

Regions that are SOM depleted due to cropping during the past 50–100 years may benefit from improved conservation management. The simulations reported in this paper for Sterling, CO all sequestered C because the soils were C depleted from ~50 years of conventional winter wheat/fallow cropping. Modifying the tillage management to no till winter wheat/fallow led to C sequestration in these C depleted soils. No till also increases water storage which can facilitate reduction of fallow periods and provide additional benefits of increased yields and higher SOM storage rates. DAYCENT simulations suggest that increasing cropping intensity and N application rates do not necessarily lead to higher N_2O emissions or lower CH_4 uptake rates but there is little observational evidence to support this.

The level of soil C response to conservation management improvement is dependent on how degraded the land is when the improved practices are implemented. The soils used for model validation (Fig. 1) were previously covered with native vegetation and began losing C upon implementation of winter wheat/fallow cropping in 1970 although no till lost C at a lower rate than conventional till (Doran et al., 1998). Even the native grass showed lower C values in 1992 compared to 1970, possibly due to changes in grass species composition (Doran et al., 1998). These results emphasize the importance of initial conditions. The Sterling soils (Fig. 3) were storing C because they were initially C depleted due to historical winter wheat/fallow cropping whereas the Sidney soils were broken from native sod and were presumably C saturated. Long term simulations of C depleted soils suggest that the rate of C storage decreases sharply after ~10–50 years of improved management and that N_2O emissions from agricultural systems increase as soils become C saturated (Del Grosso et al., 2001).

The effects of land use on net greenhouse gas exchanges can be evaluated using an absolute or relative standard. On the absolute scale, agricultural systems will probably always be net greenhouse gas sources under a full accounting that includes the factors explored in this paper as well as fossil fuel emissions associated with herbicide and pesticide manufacture and transport, plowing, harvesting, crop transport, etc. But from a 'business as usual' standard, some agricultural soils can become a smaller net greenhouse gas source upon change of management. When 'business as usual' is the native condition agriculture is expected to be an absolute and relative net greenhouse gas source. Further modeling and observational data are needed to describe optimal cropping and fertilizer application schedules that will lead to the greatest net benefits after accounting for crop yields and the net flux of greenhouse gases.

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