DISSERTATION

REFINEMENT, TESTING, AND APPLICATION OF THE DAYCENT MODEL TO INVESTIGATE ECOLOGICAL IMPACTS OF AGRICULTURE

Submitted by
Stephen J. Del Grosso
Graduate Degree Program in Ecology

In partial fulfillment of the requirements
for the degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Fall, 2002

UMI Number: 3075351

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

COLORADO STATE UNIVERSITY

November 5, 2002

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY STEPHEN DEL GROSSO ENTITLED REFINEMENT, TESTING, AND APPLICATION OF THE DAYCENT MODEL TO INVESTIGATE ECOLOGICAL IMPACTS OF AGRICULTURE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Gary Peterson

Keith Paustian

Arvin Mosier

Co-adviser, Dennis Ojima

Adviser, William Parton

Department Head/Director, Ingrid Burke

ABSTRACT OF DISSERTATION

REFINEMENT, TESTING, AND APPLICATION OF THE DAYCENT MODEL TO INVESTIGATE ECOLOGICAL IMPACTS OF AGRICULTURE

Reliable models are necessary to assess the ecological impacts of different land management options. The DAYCENT terrestrial ecosystem model was improved by reworking the soil organic matter decomposition submodel, revising the plant growth routines to make net primary productivity (NPP) simulations more mechanistic, and adding features to increase model versatility. DAYCENT was extensively tested using data from various global sites representing a range of vegetation types and land management alternatives. The model reliably simulated differences in mean values among sites/treatments for soil organic matter (SOM), grain yields, CH_4 uptake, and N_2O emissions. DAYCENT was also able to mimic the observed within site annual and seasonal patterns for grain yields, soil water content, soil temperature, soil mineral N levels, and trace gas fluxes.

Sequestration of CO_2 in SOM has been suggested as a means to compensate for anthropogenic greenhouse gas (GHG) emissions. However, changes in land management that affect SOM levels also will affect fluxes of two important non-CO_2 GHG's, N_2O and CH_4. To accomplish a full GHG accounting, the model was used to compare the effects of climate, vegetation cover, land management, and soil type on GHG_{net}. GHG_{net} was defined as the integrated GHG effect of CO_2 fluxes, N_2O emissions, CH_4 uptake, and the CO_2 costs of N fertilizer production. Model results suggest that GHG_{net} in dryland systems can be substantially reduced by conversion to no till cultivation and by reducing the summer fallow period. GHG_{net} from rainfed or irrigated intensive cropping systems can be reduced by conversion to no till and by utilizing precision fertilizer application. The land management changes recommended to reduce GHG_{net} will maintain or increase overall crop yields. DAYCENT should be one of many tools used to assess the effects of human activity on C and N cycling, regional and global climate, and biodiversity.

Stephen J. Del Grosso
Graduate Degree Program in Ecology
and Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, CO 80523
Fall 2002

Table of Contents

ACKNOWLEDGEMENTS

I can't say enough to thank my committee members for supplying the resources and encouragement required to complete this dissertation. The numerous opportunities Bill Parton, Dennis Ojima, and Arvin Mosier provided to travel and present research results to various domestic and international audiences were as fun as they were educational. Gary Peterson and Keith Paustian shared data and insights, and kept model simulations grounded in reality. In addition to providing physical resources, interacting with committee members initiated relationships with numerous individuals in the climate change, biogeochemistry, and crop science communities.

Becky Techau, Cindy Keough, and Jonathon Straube provided essential administrative, technical, and miscellaneous services. Without Cindy's programming skills model improvements and regional simulations would not have been possible. Jonathan solved countless computational problems and always made sure that posters printed successfully. Becky ensured that tasks were accomplished in a timely and professional manner and kept things running as smoothly as possible.

Manuscripts were reviewed and improved by Marci Koski and Harold Fraleigh during endless sessions at the pub. Marci was also nice enough to lend her power point expertise so that my presentations looked much better than if left to my own devices.

Lastly, I want to thank the following agencies for providing funds for support, travel, and salaries: The US Environmental Protection Agency, The National Science Foundation, and the US Department of Agriculture.

CHAPTER 1

INTRODUCTION

Since the industrial revolution, human activity has profoundly altered flows of carbon (C) and nitrogen (N) and the reservoirs of biologically reactive compounds of these elements. Reactive N from anthropogenic sources exceeds biological N fixation (Galloway and Cowling, 2002) and atmospheric concentrations of greenhouse gases have reached levels not present on Earth since at least before 420,000 years ago (IPCC, 2001). In addition to being a primary greenhouse gas, CO_2 is biologically active in that it is a raw material for photosynthesis and influences stomatal conductance and water losses from transpiration. Conversion of native ecosystems to farmland, urbanization, and industrialization not only alters local conditions but also has regional and perhaps global impacts on climate and nutrient availability. Human activities that perturb the Earth system can thus be divided into three major categories: increased fixation of important nutrients into biologically reactive form, increased greenhouse gas levels from combustion of reduced C and emission of N oxides, and land use/vegetation cover changes. These forcings strongly influence biodiversity, species composition, climate patterns, and many other biological and environmental parameters.

Agriculture is the most important anthropogenic source of increased nutrient availability for biological systems. Before fertilizer use became popular most terrestrial ecosystems were N limited and N was supplied by biological N fixation and lightning, both of which convert inert atmospheric N_2 to biologically reactive ammonia (NH_3). The discovery and implementation of the Haber-Bosch process in the 20^{th} century allowed humans to convert N_2 to NH_3 in an economically feasible manner. Widespread use of fertilizer helped bring about the green revolution and greatly increased crop yields. However, ~50% of the N applied to soils is emitted as N oxide gas or is leached into streams or groundwater (Galloway and Cowling, 2002). Nutrients in ground water and stream flow cause eutrophication in aquatic systems. Higher concentrations of N oxides in the atmosphere contribute to the greenhouse effect and result in increased N inputs from atmospheric deposition in seemingly pristine ecosystems. Increased N availability enhances growth of some organisms but most ecosystems evolved under N limiting conditions so N fertilization often favors invasive species and decreases native biodiversity. In addition to agriculture, fossil fuel combustion, industrial processes, and lawn fertilization contribute to anthropogenic N oxide emissions. Agriculture also makes a significant contribution to the anthropogenic greenhouse effect. Fossil fuel burning is the major source of anthropogenic CO_2 emissions, but agriculture is an important source of N_2O and CH_4 and can be a source or sink of CO_2. The atmospheric concentrations of CH_4 and N_2O are much smaller than CO_2 but these gases contribute to the net greenhouse gas (GHG) effect because they are more efficient at trapping long wave radiation than CO_2 on a per molecule basis.

This research focuses primarily on the effects of agriculture on GHG fluxes and secondarily on the fate of reactive N that is added to cropped soils. Agriculture is responsible for ~20% of the global GHG effect and for the majority of the anthropogenic reactive N fixation. To accurately assess the impacts of agriculture an integrated approach that combines observed data and modeling is required. Changes in concentrations of GHG's in the atmosphere can be accurately measured and are well established but the fluxes of gases that lead to these changes are uncertain. Plot scale measurements can provide useful data on small scale C and N flows, but the sampling intensity required to measure fluxes from all agricultural systems is not feasible. Therefore, models are required that assimilate relations derived from plot level data to calculate regional and global C and N fluxes.

Many types of ecosystem models have been developed to serve a variety of purposes and incorporate different assumptions. Highly mechanistic models aid in the understanding of the biophysical processes that drive important ecological variables. For example, *ecosys* (Grant, 1997) simulates C and N flows on the small time/space scales at which these processes occur. Microbial and plant biomass are explicitly modeled and processes such as gas and solute transport of biochemical reactants and products are simulated. Simpler models simulate C and N flows without explicitly representing all of the physical, biological, and chemical processes. For example, GLO-PEM (Global Production Efficiency Model) uses satellite derived photosynthetically active solar radiation (PAR) and climate data to simulate net primary productivity (NPP) at large scales without simulating soil nutrient availability (Prince and Goward, 1995). The CEVSA Potential Production Model is of intermediate complexity and uses daily precipitation and climate data to simulate soil organic carbon (SOC), NPP, and energy and water fluxes within the atmosphere-vegetation-soil system (Cao and Woodward, 1998). The disadvantage of highly complex models is that they are difficult to parameterize and consequently difficult to apply beyond the plot scale while simple models are over-generalized and will likely yield misleading results for at least some sites.

A primary objective of the modeling approach described in this dissertation is to identify key drivers of the processes that result in C and N flows and to quantitatively relate these processes to model drivers that are readily available. In this way, models integrate observations and theory and generate testable predictions regarding the state of the system and flows to and from the system. Another major objective is to provide a tool to inventory GHG fluxes from agricultural systems at the national level and to identify land management practices that are likely to decrease GHG emissions and reactive N inputs.

The DAYCENT ecosystem model is appropriate for this research because driving variables required to run the model and data to develop and test the model are readily available. DAYCENT is the daily time step version of the CENTURY model and is of intermediate complexity. CENTURY was developed in the 1970's to investigate the short and long term interactions between climate and land use change, NPP, soil organic carbon (SOC) levels, and other ecological parameters. Monthly average precipitation and maximum/minimum temperature, vegetation, land management, and soils data are required to run the model. CENTURY was parameterized based on vegetation and soils data from grassland ecosystems but has been shown to reliably simulate NPP and SOC in various managed and native systems worldwide. The soil organic matter cycling submodel used in CENTURY and DAYCENT has been incorporated into other models (e.g. Gijsman et al., 2002). DAYCENT was developed to fulfill a need to simulate trace gas (N_2O, NO_x, CH_4) fluxes from terrestrial systems. Trace gas fluxes are ephemeral and show high temporal variability so a model that runs on a daily time step or finer is required to adequately simulate these flows. DAYCENT uses the same vegetation and land management inputs as CENTURY but also needs daily precipitation and maximum/minimum temperature as well as more detailed soil information. Both DAYCENT and CENTURY can be run on plot, regional, and global scales provided input data at an appropriate resolution is available.

This research illustrates hypothesis development and testing in the context of modeling. The approach encompasses a hierarchy of hypotheses, some of which are more properly called model assumptions. The basic model assumption is that the primary controls on C and N flows are climate, vegetation type, land management, and soil properties. Furthermore, the processes that result in these flows can be quantitatively represented and incorporated into models that use readily available inputs. Qualitative hypothesis derived from these assumptions include:

1. CO_2 emissions from soils can be predicted based on labile SOC levels, soil temperature, and soil water content.

2. N gas losses from soils increase as N availability and N cycling increase.

3. Uptake of atmospheric CH_4 is primarily driven by soil gas diffusivity and undisturbed soils absorb more CH_4 than similar cropped soils.

4. Summer fallow and conventional till cultivation deplete soil of SOC

5. Soils that are depleted of SOC can become a sink for atmospheric CO_2 upon land use change.

6. GHG emissions from agricultural soils can be reduced without reducing crop yields.

7. Increased SOC storage will result in decreased N gas losses.

8. N Leaching increases as soil particle size increases and conversion to no till will increase leaching.

Hypotheses were tested by comparing model outputs with observed data. Implicit in the hypotheses is the claim that the relationships represented in the model are general so the model was tested with data from diverse native and managed systems. The soil organic matter (SOM) decomposition submodel and some data points for the CH_4 oxidation submodel were tested directly using observed values of soil water content and temperature for submodel inputs. All other outputs were tested using the full model and observed data that was not used for model development. Qualitative hypotheses were generated by performing model simulations for particular sites using appropriate land management and vegetation cover assumptions. Methods to evaluate whether hypotheses were supported or refuted included comparison of time series of observed and simulated values for a particular site or treatment, comparison of mean observed and simulated values across sites and treatments, and comparing competing models with observed data.

Chapter 2 describes in detail the development and testing of a submodel for CO_2 emissions from SOC decomposition. Chapter 3 outlines the changes included in the latest version of DAYCENT and summarizes results from model testing with data from various global sites. Chapter 4 compares simulated and observed N_2O fluxes and describes how soil texture, precipitation, and land management influence simulated N_2O, N_2, and NO_x emissions for dry land and irrigated agriculture. Chapters 5-8 emphasize net GHG accounting. GHG_{net} is defined as the sum of the greenhouse forcings of CO_2, CH_4, and N_2O fluxes in the units of CO_2-C equivalents. Chapter 5 includes a detailed description of DAYCENT and tests the ability of the model to simulate soil water content, temperature, mineral N concentration and N_2O fluxes from grassland and irrigated agricultural soils. This chapter also investigates the effects of alternative tillage practices and crop rotations on net greenhouse gas fluxes, crop yields, and N leaching for a dry Colorado soil and a wetter midwestern soil. Chapter 6 presents results of model tests for SOC, N_2O emissions, CH_4 uptake, and crop yields. It also discusses the effects of decreasing the summer fallow period in dry agricultural systems on net greenhouse gas fluxes. Chapter 7 describes the first DAYCENT simulations conducted at the regional scale. Net greenhouse fluxes and crop yields under current and improved management were simulated at the 0.5° scale for a portion of the Great Plains. Chapter 8 investigates how plant N uptake, N leaching, and total N gas losses in the US Corn Belt respond to changes in soil texture and land management. Chapter 9 summarizes comparisons with data that support/refute hypotheses and discusses model strengths and limitations.

This dissertation is the product of a collaborative effort from scientists representing various public and private organizations. Individuals specializing in soil science, crop science, ecology, computer science, biogeochemistry, and other disciplines were necessary for this research. The author integrated data and ideas from diverse sources to improve, test, and apply DAYCENT in unique ways. A high degree of collaboration is necessary because of the complexity of the systems the model is intended to represent. The data used to test the model for a single site rests on the work of numerous scientists and technicians. As a result of having resources and personnel to work with, the author was able to improve the SOC decomposition submodel, test the model using various data sets, and apply the model to gain novel insights into the effects of land management on net GHG emissions and biologically reactive N losses. This research should be considered successful to the extent that it increased understanding of the connections between the components of the Earth system and generated testable hypotheses.

References

Cao, M.K. and F.I. Woodward. 1998. Net primary ecosystem production and carbon stock of terrestrial ecosystems and their response to climate change. Global Change Biology 4: 185-198.

Galloway, J.N. and E.B. Cowling. 2002. Reactive nitrogen and the world: 200 years of change. AMBIO 31: 64-71.

Gijsman, A.J., Hoogoonboom, G., Parton, W.J. and P.C. Kerridge. 2002. Modifying DSSAT crop models for low input agricultural systems using a soil organic matter-residue module from CENTURY. Agronomy Journal 94: 462-474.

Grant, R.F. 1997. Changes in soil organic matter under different tillage and rotation: Mathematical modeling in ecosys. Soil Science Society of America Journal 61: 1159-1175.

Intergovernmental Panel on Climate Change (IPCC). 2001 Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK.

Prince, S.D. and S.J. Goward. 1995. Global primary production: a remote sensing approach. Journal of Biogeography 22: 316-336.

CHAPTER 2

MODELING CO_2 EMISSIONS FROM DECOMPOSITION OF SOIL ORGANIC CARBON

S.J. Del Grosso, S.J., W.J. Parton, A.R. Mosier, E.A. Holland,
E. Pendall, D.S. Schimel & D.S. Ojima.

Abstract

Gas flux data from rangeland soils that included a large number of measurements at low temperatures were used to model soil CO_2 emissions as a function of soil temperature and water content. Our temperature function predicts that Q_{10} values vary inversely with temperature and that soil organic matter decomposition is significant below 0 °C. Independent data representing a broad range of ecosystems and temperature values were used for model testing. The effects of plant phenology, differences in substrate availability among sites, and water limitation were accounted for so that the temperature equation could be fairly evaluated. Our variable Q_{10} model agreed closely with observed Q_{10} values over a wide range of temperatures (r^2=0.59) and was superior to best fitting constant Q_{10} and linear models for the validation data set using the Akaike Information Criterion (*AIC*). Our temperature equation explained 16-85% of the observed intra-site variability in CO_2 flux rates from the soils that were tested but including our water stress factor yielded a stronger correlation than temperature alone only in the dryland soils.

Introduction

Exchanges of carbon (C) among the atmosphere, biota, soil, and water influence essential physical and biological processes from organismal to global scales. Respiration of soil organic carbon (SOC) by microbes and other soil organisms releases 50-75 Pg of CO_2-C to the atmosphere annually, ~10 times the annual emissions from burning fossil fuels (primary ref for this ??). Accurate models of soil respiration are needed to calculate net ecosystem exchange (NEE) rates for different natural and managed systems. NEE is the net flux of C in or out of a system after accounting for CO_2 fixation (photosynthesis), respiration, depositional inputs of organic C, and erosional losses of organic C. NEE calculations help assess the degrees to which natural and managed systems are sources or sinks of C. Understanding the primary controls of soil respiration is important because SOC represents a large C sink that is subject to perturbations in response to natural and anthropogenic forcings. An objective of this paper is to quantify the temperature and water controls on soil respiration. Reliable models of soil CO_2 fluxes can be used to project how changes in land use and climate will affect SOC levels and atmospheric CO_2 concentrations.

We describe the latest heterotrophic respiration submodel used in the DAYCENT and CENTURY ecosystem models. DAYCENT (Del Grosso et al. 2001; Kelley et al. 2000; Parton et al. 1998) and CENTURY (Parton et al 1994; Metherell et al. 1993) simulate plant growth, soil C and nitrogen (N) flows, and other ecosystem parameters. Heterotrophic respiration in soils is primarily a function of substrate quality and quantity (Janssens et al. 2001), soil temperature (Katterer et al. 1998), soil water content (Leiros et al. 1999; Davidson et al. 1998), microbial community (Holland et al., 2000), and acidity (Walse et al. 1998). Most SOC decomposition models account for differences in substrate quality and quantity by simulating different SOC pools with varying maximum decay rates (e.g. Coleman & Jenkinson 1999; Parton et al.1994). In these types of models, maximum decay rates for each pool are usually attenuated using functions involving air or soil temperature, precipitation, or soil water potential (Burke et al. submitted). Walse et al. (1998) modeled decomposition of labile C as the growth rate of bacteria and decomposition of recalcitrant material as the growth rate of fungi using air temperature, soil moisture, and soil acidity as driving variables. Alternatively, Pastor and Post (1986) linked decomposition to NPP via N availability and assumed that decomposition is controlled by actual evapotranspiration (AET) and litter lignin and N concentrations.

Our primary goal was to improve the original temperature equation for decomposition used in the CENTURY ecosystem model (Parton et al. 1987). Previous decomposition models have been limited by a paucity of observations of CO_2 flux at freezing and sub-freezing temperatures (Katterer et al. 1998) and by assumptions that microbial activity in frozen or snow covered soils is negligible (Fahnestock et al. 1999). However, recently collected field data show that significant CO_2 flux rates can occur at zero and sub-zero temperatures (Fahnestock et al. 1999; Brooks et al. 1996; Sommerfeld et al. 1996). Many models (e.g. Raich & Potter 1995) use a constant Q_{10} temperature equation but Q_{10} values often vary depending on temperature range (Xu & Qi 2001; Holland et al. 2000; Lomandeer et al. 1998). Kirschbaum et al. (1995) compared how well simulated Q_{10} values agreed with Q_{10} values from observed CO_2 flux data. The best fitting models showed low (1-3) Q_{10} values at temperatures greater than 20 °C and high (8-10) Q_{10} values at 0 °C. Predicted Q_{10} values at low temperatures were limited by a lack of data for sub-0 °C temperatures and large variability in data from 0-5 °C. Field data collected over the past 5-10 years that included a large number of observations of CO_2 flux at sub-freezing temperatures yielded similar Q_{10} values at high temperatures but suggest that previous models overestimated Q_{10} values by a factor of ~1.5-2 at temperatures near 0 °C. Our model developed with this new data is likely to be more general than other models because it allows sensitivity of decomposition to vary with temperature and the data used to build and test the model included a large number of observations at low temperatures.

This paper describes the development and testing of a variable Q_{10} model and outlines a formal procedure for model comparison. Gas flux, soil temperature, and soil water content measurements from native short grass steppe soils were used for model building. Similar measurements from various native and disturbed systems were used for model testing. The temperature effect on measured soil CO_2 emissions can be confounded by site factors such as litter quality (Wang et al. 2000) and seasonal NPP patterns (Hogberg et. al. 2001) so site/season factors were accounted for when building and testing the model. We assumed that moisture stress can limit decomposition rates in dryland systems. The presented temperature equation was compared with alternative equations using the conventional r^2 parameter and the Akaike Information Criterion (*AIC*). *AIC* combines elements of inferential statistics and information theory and is useful for model comparisons because it quantifies the amount of information that is lost when a model is used to approximate an observed phenomenon. We show that our model is superior to alternative models using statistical criteria and that our temperature equation yields Q_{10} values that agree closely with Q_{10} values calculated from independent data over a wide range of temperatures.

Methods

Gas flux and ancillary measurements

The new data reported in this paper were collected from native, fertilized, and plowed shortgrass steppe soils and winter wheat/fallow fields in northeastern Colorado, and a subalpine meadow in Wyoming. The shortgrass steppe measurements were taken from 1992-1996 in plots representing different soil texture classes and fertility levels at the Central Plains Experimental Range (CPER) and the winter wheat/fallow measurements were taken on private land ~20 km southeast of the CPER during the same time period. The CPER (40 °8'23"N, 104°45'15"W) is located ~60 km northeast of Fort Collins, CO and average annual precipitation and temperature are ~32 cm and ~9.5 °C, respectively (Mosier et al. 1991; 1996; 1997). The subalpine meadow (Mosier et al., 1993) has mean annual precipitation and temperature of ~100 cm and ~ -0.5 °C, respectively, and was sampled in 1991 and 1992. The plots were established at the USDA/Forest Service Glacier Lake Ecosystem Experiments Site (GLEES) in the Snowy Range of the Medicine Bow mountains (41 °20'N, 106°20'W, elevation ~3182 m) in southeastern Wyoming ~65 km west of Laramie. At the Colorado and Wyoming sites PVC pipes (inside diameter=20.3 cm) were driven 8 cm into the soil within the plots to establish permanent gas flux measuring anchors. On sampling days, usually once per week, a 7.5 cm high closed, vented chamber was fitted onto the anchors and gas samples were extracted with a syringe at 0, 15, and 30 minutes after the chambers were attached. Concentrations of CO_2 were measured by gas chromatography within 6 hours of sampling and gas flux was calculated based on changes in CO_2 concentration as a function of time. Adjacent to the permanent anchors, soil temperature (T_{soil}) was measured at 5 cm depth with a handheld digital thermometer and six soil cores (inside diameter=2.5 cm, depth=15 cm) were combined, weighed, and oven dried so that bulk density and volumetric soil water content could be calculated.

Data sets used for model development and testing

Winter season data from the native shortgrass steppe soils were used to parameterize the temperature equation while year-round data from these soils normalized by season were used to parameterize the water equation. Two data sets were compiled for model validation. One, designated the temperate data set, included data from the managed fields in Colorado (plowed/fertilized pastures and winter wheat/fallow) previously described. This data set also included observations from winter wheat/fallow fields in western Nebraska (Kessavalou et al. 1998), alpine meadow and forest in Wyoming (Mosier et al. 1993) tall grass prairie soils in Kansas (), agricultural fields in Michigan (Robertson et al. 2000), mixed deciduous forests in Massachusetts (Savage & Davidson 2001), and a beech forest in Germany (Brume 1995). A subset of this data set, designated the heterotrophic data set, was extracted to compile measured CO_2 flux rates that were due almost entirely to SOC decomposition because plots were kept vegetation free. Herbicides were applied to the winter wheat/fallow fields during the fallow season, some shortgrass steppe plots were maintained vegetation free by plowing, and 15 meter diameter gaps were cut out of the beech forest and kept vegetation free.

The data used for model building and the temperate data set used for model testing were normalized by site and season so that the average flux was 1 unit at 12.5 °C for the growing and non-growing seasons. We normalized by site to account for differences in CO_2 flux rates that are driven by factors such as labile C availability and by season to account for the effect of plant phenology on measured flux rates. This was done for each site by dividing each data point from the growing season by the average growing season flux in the interval from 10-15 °C and dividing each data point from the non-growing season by the average non-growing season flux in the interval from 10-15 °C .

For the grassland, deciduous, and annually cropped systems the growing season was defined as May-October and the non-growing season as November-April. For the winter wheat/fallow rotations the growing season was the months from wheat planting to harvest and fallow months were designated non-growing season. All the observations from the beech forest used in this analysis were taken during the summer months. Measurements taken within the beech forest stand were assumed to be growing season and measurements taken in vegetation free gaps within the stand were classified non-growing season.

Model assumptions

We assumed that the amount of substrate controls the maximum decomposition rate and that this can be reduced by soil temperature, moisture stress, and pH. Our submodel quantifying the effects of soil temperature and water content on respiration assumes that labile C availability is known from measurements or is simulated by a model. We assumed that measured respiration rates during the non-growing season were due primarily to SOC decomposition while both decomposition and root respiration made significant contributions to measured flux rates during the growing season. The majority of measured heterotrophic CO_2 emissions are from decomposition of the more labile C pools (Schimel et al. 1994; Trumbore et al. 1990). Consequently, we would not necessarily expect our temperature equation to apply to decomposition of the more recalcitrant fractions of SOC, which may have a less sensitive temperature response (Liski et al. 1999).

Model development

Winter season CO_2 flux data from the native shortgrass steppe soils were used to quantify the effect of temperature on SOC decomposition while winter and summer data normalized by season were used to parameterize the water equation. These factors are simply multiplied in our heterotrophic respiration (R_H) submodel:

$$R_H = F(T_{soil})*F(RWC)$$

where R_H is the combined effect of water and temperature on decomposition. $F(T_{soil})$ is the temperature effect normalized to 1 at 30 °C:

$$F(T_{soil}) = 0.56+(1.46*\arctan(\pi*0.0309*(T_{soil}-15.7)))/\pi$$

and F(RWC) is the water effect normalized to 1 at RWC = 100%:

$$F(RWC) = 5*(0.287+(\arctan(\pi*0.009*(RWC-17.47)))/\pi)$$

where RWC is the measured soil relative water content.

Figure 2.1a shows the response of winter season CO_2 emissions to soil temperature (T_{soil}) when water was not strongly limiting and $F(T_{soil})$, our variable Q_{10} arctangent function. Figure 2.1b shows the response of normalized CO_2 emissions to RWC when temperature was not strongly limiting and our water function, F(RWC). The overall model explained a reasonable amount of the variability in normalized CO_2 emissions for the data set used for model building (Figure 2.1c). Using the entire model building data set, the primary effect of temperature was significant (r^2=0.27), the primary effect of water was insignificant (r^2=0.01), and the interaction between water and temperature was significant (r^2=0.47). The primary effect of water was significant when data points subject to temperature limitation (T_{soil} < 15 °C) were eliminated (Figure 2.1b), providing further evidence that temperature and water interact to control decomposition rates in these soils.

Our water function uses RWC as a metric for soil water availability because it accounts for differences in water stress on biological activity at a given water content driven by soil physical properties. Volumetric water content was converted to relative RWC using the following:

$$RWC = (W-WP)/(FC-WP)$$

where W = measured volumetric soil water content, WP = wilting point, and FC = field capacity. FC and WP were estimated for each soil using soil texture data and time series data of soil water content. Both WP and FC tend to increase as clay content increases (Saxton et al. 1986).

Model Comparisons

Competing models and model comparison criteria

We compared our arctangent model with the original CENTURY equation (Parton et al., 1987) and with the best fitting exponential model because the exponential function is often used to quantify the effect of temperature on decomposition (Kirschbaum, 1995). We also included the best fitting linear model in the comparison because the linear function yields a variable Q_{10} and the temperature equation in some models is virtually linear over the biologically active temperature range (e.g. Walse et al.

1998). To fairly compare the alternative temperature equations, we accounted for the effects of site specific factors, (e.g., substrate availability), plant phenology, and water limitation on measured soil respiration rates.

Simulated and observed Q_{10} values as well as CO_2 flux rates were used in model comparisons. We defined Q_{10} as the ratio of the rate of a process at 5 °C above a particular temperature to the rate of the process at 5 °C below that temperature. For an exponential function, $y = a*e^{(bx)}$, the Q_{10} does not vary with temperature and can be calculated as $Q_{10} = e^{(10b)}$. Q_{10} values were calculated for the two validation data sets by sorting the data by temperature and deriving the best fitting exponential function for normalized CO_2 respiration as a function of temperature for overlapping 10 °C ranges centered at integer temperature values in the range from $^-$5-25 °C. For the variable Q_{10} models (arctangent, original CENTURY, linear), Q_{10} values were calculated by dividing the functional output at 5 °C above the temperature range midpoint by the functional output at 5 °C below the temperature range midpoint for the same integer temperature midpoints for which observed Q_{10} values were calculated.

In addition to the correlation coefficient (r^2) we also used Akaike's Information Criterion (*AIC*) and Akaike weights (w_r) to compare models. *AIC* combines the Kullback-Leibler (K-L) discrepancy, the dominant paradigm in information theory, with maximum likelihood estimation, the dominant paradigm in statistics (Burnham and Anderson 1998). Traditional statistical inference is concerned with the probability that a data set would be observed given that a model (hypothesis) is correct. Conversely, inference based on likelihood is concerned with the likelihood of a model being superior to competing models when compared using a set of observations. The K-L distance is appropriate for model comparisons because it quantifies the information that is lost when a set of model outputs, q, is used to approximate a true distribution, p (Sakamoto 1986). The absolute K-L distance cannot usually be calculated for a particular model because truth (e.g., the true relationship between soil temperature and decomposition) is unknown. However, Akaike (1973) showed that likelihood can be used to estimate the relative K-L distance for alternative models and to determine which competing model is closest to truth as manifested by a particular data set. *AIC* estimates the expected relative K-L distance and the model with the lowest AIC value is considered the best model. This criterion accounts for goodness of fit as well as over-fitting the data because *AIC* includes a penalty proportional to the number of free parameters in the model. *AIC* is calculated as:

$$AIC = -2\log(L(\theta_r)) + 2K$$

where $L(\theta_r)$ is the maximized likelihood estimate for a model and its parameters, θ_r, compared to a data set, and K is the number of parameters in the model that were allowed to vary when fitting the model to a particular data set. $L(\theta_r)$ is calculated as:

$$L(\theta_r) = -0.5\ln\frac{\sum_{n=1}^{N}\left(\ln(obs) - \ln(sim)\right)^2}{N}$$

where N is the number of data points with observed and simulated values. To compare models Akaike weights (w_r) were calculated:

$$w_r = \frac{e^{\left[\frac{-\Delta_r}{2}\right]}}{\sum_{i=1}^{R} e^{\frac{-\Delta_r}{2}}}$$

where Δ_r is the difference in *AIC* values etween model *r* and the model with the minimum AIC value and R is the number of models being compared. The Akaike weight of model *r* (w_r) may be interpreted as the probability that model *r* is the best model (i.e. has the minimum K-L distance) given the data set used for model testing and the designated set of competing models (Burnham & Anderson 1998).

Model comparisons

We compared our arctangent function used to represent the effect of temperature on SOC decomposition with the original CENTURY equation and with best fitting exponential and linear models. Model comparisons were performed using the heterotrophic and temperate data sets described previously. The heterotrophic data set was used because the measured CO_2 flux rates were due almost entirely to heterotrophic respiration so the ability of the models to simulate SOC decomposition would be isolated. The temperate data set was also used even though it contains measurements that are driven to a significant extent by root respiration because this allowed for model testing using a large number of data points collected from different sites.

Two methods were used to avoid confounding the effect of temperature on respiration with the effects of seasonal and site specific factors. One way is to include a site/seasonal multiplier in the respiration equation and the other is to normalize CO_2 flux rates for each site to a common value at a given temperature. Using the former method, we fit a multiplier (*M*) for the growing and non-growing seasons for each site in the following respiration equation:

$$R_{soil} = F(Tsoil)*F(RWC)*M$$

where *M* was optimized by minimizing the *AIC* for simulated versus observed CO_2 flux rates. No parameters in the arctangent function, $F(T_{soil})$, or the original CENTURY function were allowed to vary (*K*=0 in the *AIC* equation). Simulated respiration rates were calculated in a similar manner for the exponential and liner models except that in addition to *M*, the curve shape or slope parameter was also allowed to vary (*K*=1) when optimizing the exponential or linear functions.

For the analysis of the temperate data set we used the procedure described in the preceding paragraph and an alternative approach to account for water limitation and site/seasonal factors. We removed data points from the dryland systems subject to moisture stress (RWC < 40%) and normalized the remaining data to account for site/seasonal controls using the procedure described in the *Data sets used for model development and testing* section. As before, the curve shape or slope parameter was allowed to vary when fitting the exponential or linear functions, but not for the arctangent and original CENTURY functions.

Results

Table 2.1 summarizes the results of model comparisons with the two data sets. The arctangent function performed somewhat better when evaluated with the *AIC* criterion than the competing models when comparing simulated and observed CO_2 flux rates using the heterotrophic data set. The Akaike weights (w_r) imply that the liner, exponential, original CENTURY, and arctangent models have 3%, 6%, 34%, and 57% probabilities, respectively, of being the best model when compared using this data set. The r^2 and w_r values were marginally higher for the arctangent model when compared using the temperate data sets (Table 2.1). However, when observed versus simulated Q_{10} values were compared the w_r values imply that the arctangent function has a 76% probability of being the best model (Table 1). The r^2 parameter could not be calculated for the exponential using observed and simulated Q_{10} values because Q_{10} does not vary with the exponential.

Figure 2.2 provides further evidence that the arctangent function is superior for simulating the effect of temperature on decomposition. Q_{10} values predicted using the original CENTURY and new arctangent functions and Q_{10} values calculated form both data sets were plotted versus temperature range midpoint at 5 °C increments. There is a strong pattern of decreasing Q_{10} with increasing temperature for both data sets (Figure 2.2). The original CENTURY equation has the proper trend but tends to over-estimated Q_{10} values, particularly at low temperatures. Our arctangent equation is clearly less biased than the original CENTURY equation and agrees closely with the Q_{10} values calculated from observed CO_2 flux rates for both of the data sets.

Seasonal, biome and land management effects on soil respiration

We compared the M values that were optimized for growing and non-growing season at each site as previously described. The data showed strong evidence that plant phenology is a major driver of within site CO_2 flux rates and that differences in average flux rates among sites are often related to NPP and SOC levels (Figure 2.3, Table 2.2).

Excluding the alpine forest soil, the ratio of *M* values for summer compared to winter ranged from 1.6 to 2.6, suggesting that roots are responsible for a significant proportion of observed CO_2 flux rates during the growing season. Growing season *M* values tended to vary directly with NPP and non-growing season with SOC levels. The linear regression between non-growing season *M* value and SOC for the 7 sites with available SOC data yielded an r^2 value of 0.84.

The alpine meadow is in a depositional zone, has high NPP, high SOC levels and also had the highest growing and non-growing season *M* values, while the SOC depleted agricultural soils had low *M* values. Similarly, the native tallgrass prairie has higher SOC and NPP than the native shortgrass steppe and also has higher *M* values. The winter wheat/fallow fields in NE had higher *M* values than the winter wheat fallow fields in CO. The CO fields had been in production for more than twice as long as the NE fields and are depleted in SOC to a greater extent than the NE fields. The plowed pasture had a higher *M* value than the native pasture during the winter even though SOC levels were similar, probably a result of increased decomposition rates resulting from disturbance of soil aggregates.

The results in Table 2.2 show that our model generally did better (higher r^2) simulating fluxes due primarily to heterotrophic respiration (non-growing season) than fluxes that included a large proportion of root respiration (growing season). This is expected because the model was parameterized to simulate respiration from SOC decomposition. The r^2 parameter could not be calculated with temperature as the independent variable for the alpine meadow and forest during the non-growing season because the ground was covered in snow and soil temperatures did not fluctuate beyond - 1 - 1°C (Sommerfeld et al. 1996).

Discussion

We described a variable Q_{10} temperature model used to simulated SOC decomposition and showed that this model is superior to alternative models using a formal model testing procedure. Many researchers have found evidence that Q_{10} values vary with temperature range (e.g. Xu & Qi 2001; Holland et al. 2000; Lomander et al. 1998). Kirschbaum et al. (1995) compared simulated Q_{10} values from different models and from incubations as a function of temperature and showed that Q_{10} values decrease as temperature increases. Our model and the data we compiled for model testing provide further evidence that Q_{10} varies inversely with temperature but our Q_{10} values, particularly at low temperatures, are lower than those reported by Kirschbaum et al. (1995). There are several reasons for this discrepancy. The lack of CO_2 flux data at sub-freezing temperatures led to unreliable Q_{10} estimates at low temperatures. Q_{10} values reported in Kirschbaum et al. (1995) were calculated from individual studies whereas the Q_{10} values in this paper were calculated from an aggregated set of normalized data from various sites. Also, the Q_{10} values in Kirschbaum et al. (1995) were calculated from CO_2 flux from incubations in which other factors (e.g. substrate availability, moisture) were less likely to be limiting than in the field soils that we analyzed.

Model testing with two independent data sets provided evidence that our variable Q_{10} (arctangent) model is superior to the original CENTURY temperature equation and best fitting constant Q_{10} and linear models. The effects of site factors and plant phenology were accounted for when comparing models by including a site/seasonal multiplier in the model or by normalizing the data by site/season. Models were compared using a large data set that included measurements driven by heterotrophic and autotrophic respiration (temperate data set) and a data set for which measured CO_2 flux rates were due almost entirely to decomposition because the plots were maintained vegetation free. Comparisons with the heterotrophic data set provided stronger evidence that our arctangent equation is the best model than comparisons with the temperate data set. This is not surprising because the model was developed to simulated CO_2 flux from decomposition but the temperate data set included data points that were driven to a large extent by root respiration. The preponderance of the evidence (Table 2.1, Figure 2.2) supports the conclusion that the arctangent is the best model for the aggregated data used for model testing.

The r^2 criteria often did not strongly favor one model over another but the *AIC* and w_r parameters showed strong evidence that the arctangent equation is the best model when compared using observed and simulated heterotrophic CO_2 flux rates and Q_{10} values (Table 2.1). This discrepancy is due to several factors. In contrast to *AIC*, the r^2 parameter does not account for model bias. The original CENTURY equation has a strong tendency to over-estimate Q_{10} values (Figure 2.2) but it has a higher r^2 value than the arctangent function when comparing observed and simulated Q_{10} values (Table 2.1). When using *AIC* and w_r, model error is calculated as the difference between ln(observed) and ln(simulated) whereas r^2 uses non-transformed data. The effect of using the natural logarithm is that model errors at low observations are given weights proportional to errors when observations are high. The r^2 parameter tends to discount model errors when observations are low and to over-emphasize the importance of simulating high values correctly. For these and other reasons, the utility of r^2 as a tool for model comparisons has been questioned (McQuarrie & Tsai 1998).

Analysis of data from various soils supports our assumptions that substrate availability is a primary inter-site control of soil CO_2 respiration and that seasonal NPP patterns, as well as temperature, are important intra-site controls. Optimized non-growing season multipliers (*M* in Table 2.2, Figure 2.3) varied by more than a factor of two among sites and are at least partially the result of differences in substrate availability. For example, non-growing season *M* was higher for the tallgrass prairie than the shortgrass steppe and the prairie has higher SOC (~5 kgC m^{-2} vs. ~3 kgC m^{-2}). Within sites, plant phenology and temperature both strongly influenced respiration rates in most of the soils we tested. Growing season *M* values were higher than non-growing season *M* values. This implies that at a given temperature more respiration occurs during the growing season because root respiration makes a greater contribution to total flux rates. Comparison of growing and non-growing season *M* values suggests that roots are responsible for a significant portion (35-65%) of total respiration during the growing season. This is consistent with isotope data showing that ~35-50% of soil CO_2 emissions from shortgrass steppe soils during the growing season were due to decomposition (Pendall et al. in review) and ~55% of soil CO_2 emissions from temperate forests late in the growing season were due to rhizosphere respiration (Andrews et al. 1999). Similarly, radiocarbon data collected along an elevational gradient showed that SOM decomposition was responsible for ~20-50% of CO_2 flux during the growing season and close to 100% during the non-growing season (Wang et al. 2000).

For model testing purposes, we assumed that heterotrophic and root respiration have the same relative response to temperature, i.e. only scalar multipliers were used to distinguish growing season from non-growing season flux rates. However, we acknowledge evidence that root respiration is more sensitive to temperature changes in the 10-20 °C range than heterotrophic respiration (Boone et al. 1998). Nonetheless, data show that our equation designed to model SOC decomposition can successfully simulate temperature responses during the growing season in many soils (Table 2.2) and Q_{10} values were similar for the heterotrophic and temperate data sets (Figure 2.2).

Our water equation rarely explained more than 10% of the observed variability in respiration rates and the interaction between our water and temperature functions increased r^2 values by more than 5% compared to the temperature equation alone only for the dryland soils (shortgrass steppe and winter wheat/fallow) that were studied. We suspect that we did not detect a strong water effect in the non-dryland soils because these soils lacked a sufficient number of data points which exhibited water stress. Similarly, Boone et al. (1998) concluded that soil moisture was unrelated or weakly correlated with soil moisture content for deciduous forest soils. However, Savage and Davidson (2001) used a multi-year data set and showed that differences in precipitation patterns can explain a significant proportion of the observed variability in inter-annual CO_2 emissions from deciduous forests. We conclude that the likelihood of finding a statistically strong water effect is dependent upon the universe of data that is analyzed and that failure to do so does not mean that water is not a primary control on soil respiration rates. Overall, our data are consistent with other research (e.g. Billings et al. 1998) showing that in non-saturated soils temperature is usually a more important control than water and that the interaction between water and temperature can be important (Xu and Qi 2001; Davidson et al. 1998).

Conclusions

This paper supports the findings of other researchers that different factors interact to control soil respiration rates. Substrate availability and NPP explain a large proportion of the inter-site variability in CO_2 emission rates while temperature and plant phenology often explain a majority of the observed within site variability (Janssens et al. 2001). Our model explained between 16% and 85% of the observed within season variability in CO_2 flux rates (Table 2.2). This suggests that water and temperature are primary within site controls for some, but not all systems. Similarly, we found a correlation between SOC and potential respiration rates but differences in SOC levels among sites are not always correlated with average CO_2 flux rates and other factors such as microbial community may be important (Holland et al. 2000). But for many soils, substrate availability, plant phenology, soil temperature, and soil water availability are primary controls on decomposition rates and can be modeled reasonably well.

References

Akaike H (1973) Information theory and an extension of the maximum likelihood principle. In: Petrov BN & Csaki F (Eds) 2nd International Symposium on Information Theory (pp 267-281). Akademiai Kiado, Budapest.

Andrews JA, Harrison KG, Matamala R & Schlesinger WH (1999) Separation of root respiration from total soil respiration using carbon-13 labeling during Free-Air Carbon dioxide Enrichment (FACE). Soil Sci. Soc. Am. J. 63: 1429-1435.

Billings SA, Richter DD & Yarie J (1998) Soil carbon dioxide fluxes and profile concentrations in two boreal forests. Can. J. For. Res. 28: 1773-1783.

Boone RD, Nadelhoffer KJ, Canary JD & Kaye JP (1998) Roots exert a strong influence on the temperature sensitivity of soil respiration. Nature. 396: 570-572.

Brooks PD, Williams MW & Schmidt SK (1996) Microbial activity under alpine snowpacks, Niwot Ridge, Colorado. Biogeochem. 32: 93-113.

Brumme, R (1995) Mechanisms for carbon and nutrient release and retention in beech forest gaps. 3. Environmental regulation of soil respiration and nitrous oxide emissions along a microclimatic gradient. Plant and Soil 168-169: 593-600.

Burnham KP & Anderson DR (1998) Model selection and inference: a practical information-theoretic approach. Springer, New York.

Coleman K & Jenkinson DS (1999) ROTHC-26.3, a model for the turnover of carbon in soil: Model description and user's guide. http://www.iacr.bbsrc.ac.uk/res/depts/soils/carbon/tagree_dos.html

Davidson EA, Belk E & Boone RD (1998) Soil water content and temperature as independent or confounding factors controlling soil respiration in a temperate mixed hardwood forest. Global Change Biol. 4: 217-227.

Del Grosso SJ, Parton WJ, Mosier AR, Hartman MD, Brenner J, Ojima DS & Schimel DS (2001) Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: Schaffer M, Ma L & Hansen S (Eds.) Modeling Carbon and Nitrogen Dynamics for Soil Management (pp 303-332). CRC Press, Boca Raton, Florida.

Fahnestock LT, Jones MH & JM Welker (1999) Wintertime CO_2 efflux from arctic soils: Implications for annual carbon budgets. Global Biogoechem. Cycles. 13: 775-779.

Hogberg P, Nordgren A, Buchmann N, Taylor AFS, Ekblad A, Hogberg MN, Nyberg G, Ottosson-Lofvenius M & Read DJ (2001) Large-scale forest girdling shows that current photosynthesis drives soil respiration. Nature. 411: 789-792.

Holland EA, Neff JC, Townsend AR & McKeown B (2000) Uncertainties in the temperature sensitivity of decomposition in tropical and subtropical ecosystems: Implications for models. Global Biogeochem. Cycles 14: 1137-1151.

Janssens IA, et al. (2001) Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. Global Change Biol. 2001: 269-278.

Katterer TM, Reichstein O, Andren A & Lomander A (1998) Temperature dependence of organic matter decomposition - a critical review using literature data analyzed with different models. Biol. & Fertil. Soils. 27: 258-262.

Kelly RH, Parton WJ, Hartman MD, Stretch LK, Ojima DS & Schimel DS (2000) Intra and interannual variability of ecosystem processes in shortgrass steppe. Journal of Geophysical Research: Atmospheres. 105: 20,093-20,100.

Kessavalou A, Mosier AR, Doran JW, Drijber RA, Lyon DL & Heinemeyer O (1998) Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. Journal of Environmental Quality. 27: 1094-1104.

Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic matter storage. Soil Biol. Biochem. 27: 753-760.

Leiros MC, Trasar-Cepeda C, Seoane S & Gil-Sotres F (1999) Dependence of mineralization of soil organic matter on temperature and moisture. Soil Biol. & Biochem. 31: 327-335.

Liski J, Makela A & Westman CJ (1999) CO2 emissions from soil in response to climatic warming are overestimated - The decomposition of old soil organic matter is tolerant of temperature. Ambio.28: 171-174.

Lomander A, Katterer T & Andren O (1998) Modeling the effects of temperature and moisture on CO_2 evolution from top and subsoil using a multi-compartment approach. Soil Biol. Biochem. 30: 2023-2030.

MsQuarrie ADR & Tsai CL (1998) Regression and Time Series Model Selection. World Scientific, Singapore.

Metherell AK, Harding LS, Cole CV & Parton WJ (1993) CENTURY soil organic matter model environment, Technical documentation, Agroecosystem version 4.0. Great Plains System Research Unit Technical Report No. 4. USDA-ARS, Fort Collins, Colorado.

Mosier AR, Schimel DS, Valentine DW, Bronson KF & Parton WJ (1991) Methane and nitrous oxide fluxes in native, fertilized, and cultivated grasslands. Nature. 350: 330-332.

Mosier AR, Klemeddtson LK, Sommerfeld RA & Musselman RC (1993) Methane and nitrous oxide flux in a Wyoming subalpine meadow. Global Biogeochem. Cycles. 7: 771-784.

Mosier AR, Parton WJ, Valentine DW, Ojima DS, Schimel DS & Delgado JA (1996) CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 1. Impact of landscape and nitrogen addition, Global Biogeochem. Cycles. 10: 387-399.

Mosier AR, Parton, WJ, Valentine DW, Ojima DS, Schimel DS & Hienemeyer O (1997) CH4 and N2O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change. Global Biogeochem. Cycles. 11: 29-42.

Parton WJ, Schimel DS, Cole CV & Ojima DS (1987) Analysis of factors controlling soil organic matter levels in the great plains region. Soil Sci. Soc. Am. J. 51: 1173-1179.

Parton WJ, Ojima DS, Cole CV & Schimel DS (1994) A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Quantitative Modeling of Soil Forming Processes, Soil Science Society of America, Special Pub. 39 (pp 147-167). Madison, WI.

Parton WJ, Hartman M, Ojima DS & Schimel DS (1998) DAYCENT: Its land surface submodel: description and testing. Global Planetary Change. 19: 35-48.

Pastor J & Post WM (1986) Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles. Biogeochem. 2: 3-27.

Raich JW & Potter CS (1995) Global patterns of carbon dioxide emissions from soils. Global Biogeochem. Cycles. 9: 23-36.

Robertson GP, Paul EA & Harwood RR (2000) Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science. 289: 1922-1925.

Sakamoto Y (1986) Akaike Information Criterion Statistics. KTK Scientific Publishers, Tokyo.

Savage KE & Davidson EA (2001) Interannual variation of soil respiration in two New England forests. Global Biogeochem. Cycles. 15: 337-350.

Saxton KE, Rawls WJ Romberger JS & Papendick RI (1986) Estimating generalized soil-water characteristics from texture. Soil Sci. Soc. Am. J. 50: 1031-1036.

Schimal DS, Braswell BH, Holland EA, McKeown R, Ojima DS, Painter TH, Parton WJ & Townsend AR (1994) Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils. Global Biogeochem. Cycles. 8: 279-293.

Sommerfeld RA, Massman J & Musselman RC (1996) Diffusional flux of CO_2 through snow: Spatial and temporal variability among alpine-subalpine sites. Global Biogeochem. Cycles. 10: 473-482.

Trumbore SE, Bonani G & Wölfli W (1990) The rates of carbon cycling in several soils from AMS ^{14}C measurements of fractionated soil organic matter. In: Bouwman AF (Ed.). Soils and the Greenhouse Effect (pp 405-414). Wiley, New York.

Walse C, Berg B & Sverdrup H (1998) Review and synthesis of experimental data on organic matter decomposition with respect to the effects of temperature, moisture, and acidity. Environ Rev. 6: 25-40.

Wang Y, Amundson R & Niu XF (2000) Seasonal and altitudinal variation in decomposition of soil organic matter inferred from radiocarbon measurements of soil CO_2 flux. Global Biogeochem. Cycles. 14: 199-211.

Xu M & Qi Y (2001) Spatial and seasonal variations of Q_{10} determined by soil respiration measurements at a Sierra Nevadan forest. Global Biogeochem. Cycles. 15: 687-696.

Tables

Table 2.1. Comparisons of best fitting linear and exponential functions, the original CENTURY decomposition equation, and our new arctangent equation using Akaike weights (w_r) and correlation coefficients (r^2) for simulated versus observed CO_2 flux rates for 2 data sets and simulated versus observed Q_{10} values from both of the data sets.

	heterotrophic data (CO_2 flux)		temperate data (CO_2 flux)		combined data (Q_{10} values)	
Function	w_r	r^2	w_r	r^2	w_r	r^2
linear	0.03	0.44	0.13	0.31	0.08	0.27
exponential	0.06	0.41	0.14	0.31	0.03	
original CENTURY	0.34	0.47	0.36	0.31	0.13	0.67
arctangent	0.57	0.48	0.37	0.33	0.76	0.59

Table 2.2. Correlation coefficients (r^2) for the linear regression between our soil respiration model and measured soil respiration rates and optimized site/season multipliers (M).

vegetation type	$r^2_{\text{non-growing}}$	$r^2_{\text{growing-season}}$	$M_{\text{non-growing}}$	$M_{\text{growing-season}}$
native shortgrass CO	0.28	0.46	1.15	3.08
plowed pasture CO	0.69		1.31*	
fertilized shortgrass CO	0.52	0.31	1.42	3.07
wheat/fallow CO	0.46	0.24	0.86*	2.27
wheat/fallow NE	0.49	0.20	1.06*	3.10
tallgrass KS	0.85	0.77	2.02	5.33
continuous cropping MI	0.16	0.13	1.11	1.74
mixed deciduous MA	0.48	0.38	2.15	3.59
beech Germany	0.51	0.72	1.28*	2.36
alpine meadow WY		0.54	2.7	6.62
alpine forest WY		0.32	6.4	5.70

* indicates plots kept free of vegetation by plowing, herbicide, or tree removal.

List of Figures

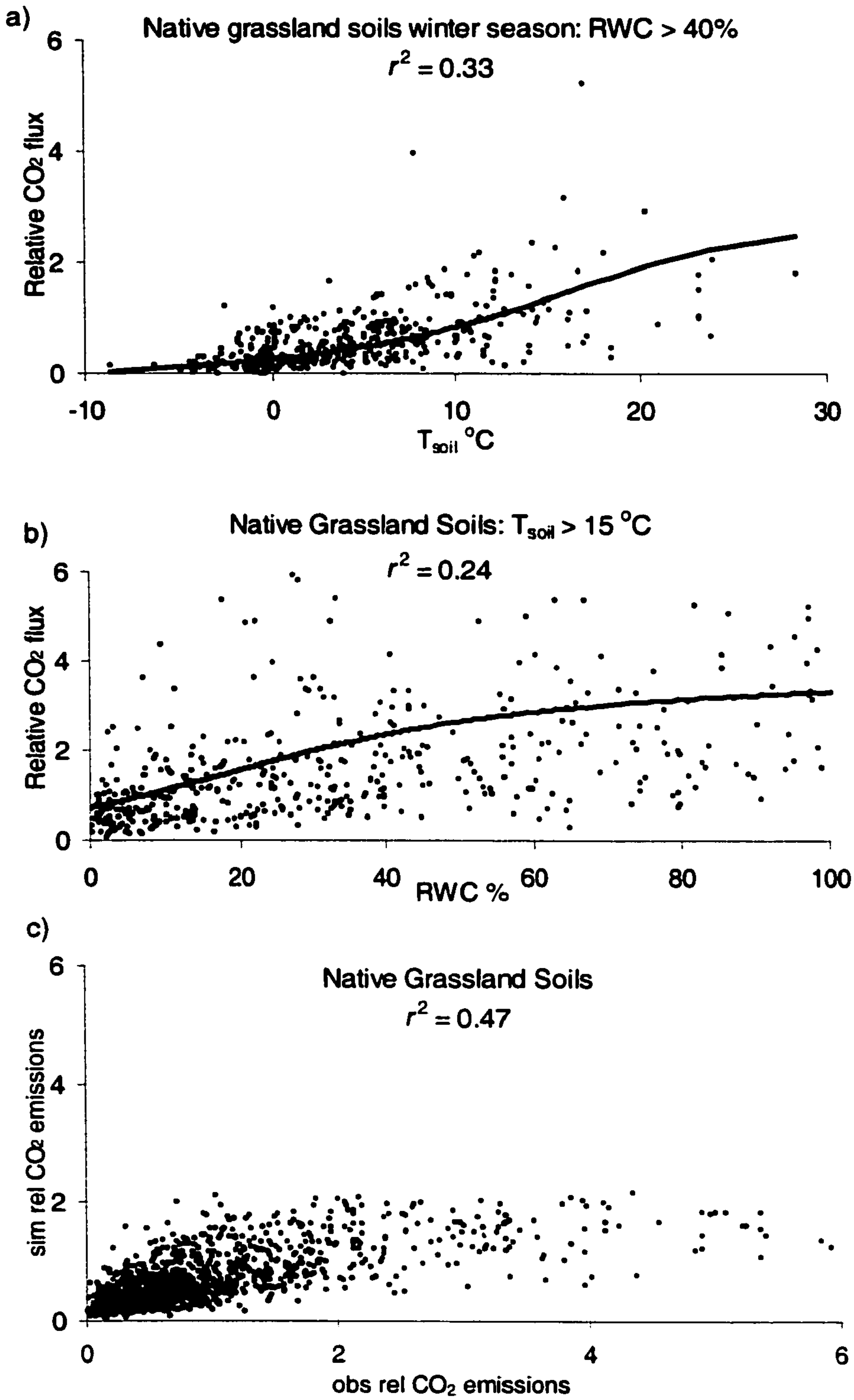

a)
Native grassland soils winter season: RWC > 40%
r2 = 0.33
Relative CO2 flux
Tsoil °C
b)
Native Grassland Soils: Tsoil > 15 °C
r2 = 0.24
Relative CO2 flux
RWC %
c)
Native Grassland Soils
r2 = 0.47
sim rel CO2 emissions
obs rel CO2 emissions

Figure 2.1

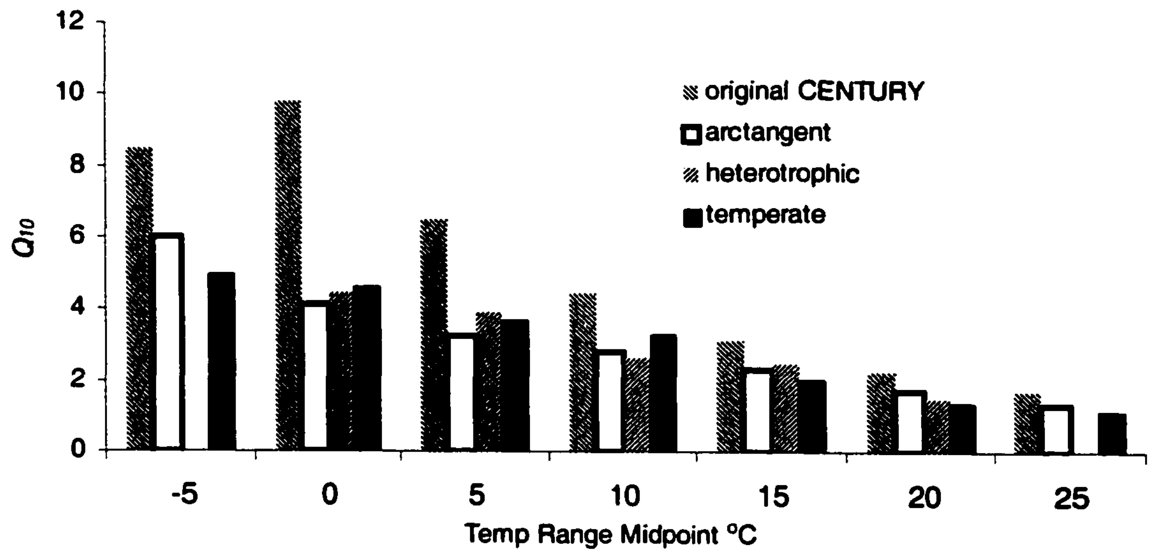


Figure 2.2

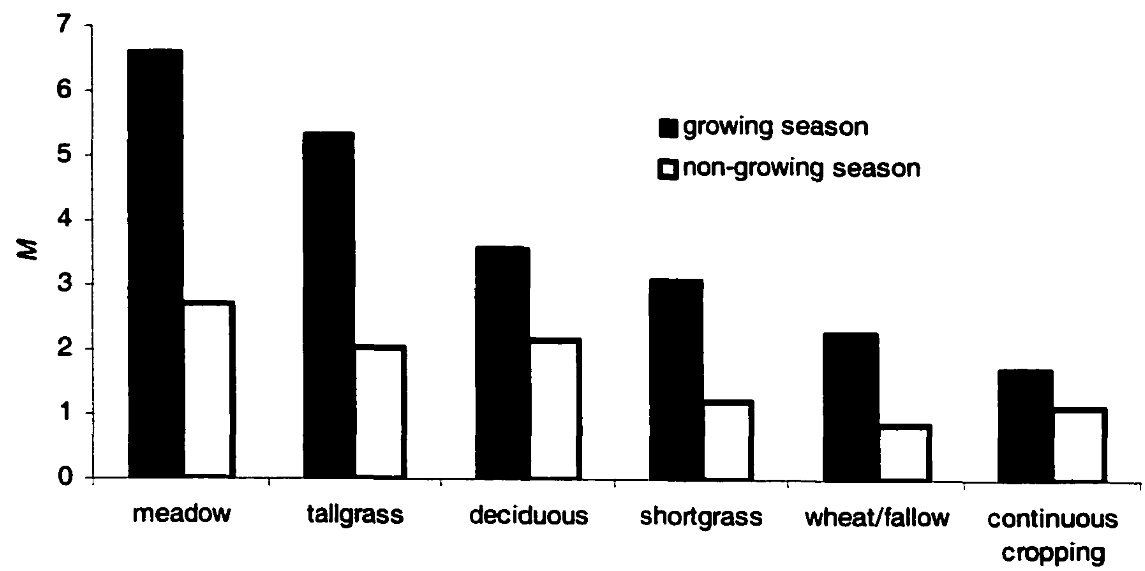


Figure 2.3

CHAPTER 3

DAYCENT: NEW MODEL DEVELOPMENTS AND VALIDATIONS

Abstract

The DAYCENT terrestrial ecosystem model simulates exchanges of C and N between the soil, atmosphere, and vegetation. New model features include the ability to vary soil pH and users may simulate a soil water table and charcoal soil C. The plant growth routines have been changed to make the model more realistic. C is now allocated among plant components based on nutrient and water stress and potential NPP rates are a function of solar radiation. The equation that represents the affect of temperature on decomposition has been modified. DAYCENT was tested using data from various global sites. Crop yields, soil C, and trace gas (N_2O and CH_4) fluxes were simulated well with the r^2 for the linear regression between simulated and observed site and treatment means ranging from 74% to 93%. Comparisons of observed and simulated time series for individual sites showed that the model captures the annual variability in crop yields (r^2 = 65% to 88%) and the daily variability in soil water content (r^2 = 73%) and temperature (r^2 = 83%) well. On the daily basis N_2O emissions were not well simulated (r^2 = 0% to 20%) and CH_4 uptake was a little better (r^2 = 10% to 40%). However the general seasonal patterns for trace gas fluxes were captured by the model, as were the site differences for these fluxes.

Introduction

Fossil fuel burning, industry, agriculture, and land use change strongly influence carbon (C) and nitrogen (N) cycling on local, regional, and global scales. Major effects of human induced changes in C and N flows include increased concentrations of greenhouse gases in the atmosphere and higher inputs of biologically reactive N in terrestrial and aquatic systems. These changes in turn influence climate, biodiversity and other environmental and biological parameters. Reliable ecosystem models are necessary to assess the extent to which different human activities alter flows of C and N. Comparing model outputs with observed data makes model weaknesses apparent and can lead to model improvement. Models can also be improved by making parameters and submodels more mechanistic and less arbitrary. This paper describes the DAYCENT and CENTURY ecosystem models and highlights new features and changes in the submodels of the latest versions of the models. We also report results of model tests comparing observed and simulated values for soil organic carbon (SOC), crop yields, nitrous oxide (N_2O) emissions, methane (CH_4) uptake, soil water content, and soil temepratature.

Model Description

DAYCENT (Del Grosso et al., 2001; Kelly et al., 2000; Parton et al., 1998) is the daily time step version of the CENTURY model (Parton et al., 1994). DAYCENT and CENTURY are used to simulate exchanges of carbon, nutrients, and trace gases among the atmosphere, soil, and vegetation for managed and native terrestrial ecosystems. The models assume that inputs of climate, soil properties, vegetation type, and land management can be used to simulate the processes that control C and nutrient flow rates.

The models can simulate N, phosphorous (P), and Sulfur (S) cycling but in many systems N is assumed to be the primary limiting nutrient. N availability controls plant growth and N losses from the system. N losses are important because gaseous N emissions affect the atmosphere's chemical and radiative properties and enhance N inputs from deposition while soluble forms of N (nitrate and organic N) contribute to eutrophication of aquatic systems. N availability is controlled by decomposition rates and by external additions of N to the system. Decomposition of soil organic matter (SOM) and plant residue results in release of mineral N which is then available for plant uptake and microbial processes that result in N gas losses. In addition to this internal cycling of N, N can be added to the system from fertilizer application, atmospheric deposition, and biological N fixation.

SOM is divided into 3 pools (active, slow, passive) in DAYCENT and CENTURY based on maximum decomposition rates. Actual decomposition rates are controlled by abiotic soil temperature/water factors, soil physical properties, the C/N ratios of organic matter inputs, and disturbance events such as cultivation and burning. The submodels for plant productivity and decomposition of dead plant material and SOM are similar in CENTURY and DAYCENT. Vegetation is divided into two broad categories. One includes grasses and crops and the other trees and shrubs. Only one type of grass/crop or tree/shrub can be grown at one time. The models can simulate competition between grasses and trees when operated in the savanna mode. Net Primary Productivity (NPP) is a function of nutrient availability, soil water and temperature, shading, and vegetation type (Metherell et al., 1993). NPP is allocated among leafy, woody, and root compartments based on plant type, soil water content, and mineral N availability. C/N ratios of biomass vary within plant specific bounds based on the ratio of

N availability to N demand. As the ratio of N availability to N demand increases, the ratio of C/N decreases.

DAYCENT operates at a finer time scale and some of the submodels in DAYCENT are more mechanistic than in CENTURY. The primary motivation for developing DAYCENT was reliable simulation of N gas emissions from soils. The response of N gas emissions to soil water content and texture is non-linear and N gas emissions are highly pulse driven. It is not possible to correctly simulate the short term (daily and finer time scale) conditions that result in pulses of N gas flux using monthly scale driving variables. Consequently, DAYCENT requires daily maximum/minimum temperature and precipitation data. Soil texture, BD, and hydraulic properties must be specified for each layer of the soil profile of user-defined depth. The land surface submodel of DAYCENT simulates water flow through the plant canopy, litter and soil profile and soil temperature throughout the profile (Parton et al., 1998; Eitzinger et al., 2000).

The trace gas submodel in DAYCENT simulates N_2O, NOx, and N_2 emissions from nitrification and denitrification as well as CH_4 oxidation. N gas flux from nitrification is assumed to be a function of soil ammonium (NH_4^+) concentration, water content, temperature, and pH (Parton et al., 1996; Parton et al., 2001). Denitrification is a function of soil nitrate (NO_3^-) concentration, labile C availability, WFPS, and soil physical properties related to texture that influence gas diffusivity (Parton et al., 1996; Del Grosso et al., 2000a. Nitric oxide (NO_x) emissions from soil are a function of total N_2O emissions, a NO_x/N_2O ratio equation, and a precipitation initiated pulse multiplier (Parton et al., 2001). CH_4 uptake is controlled by soil gas diffusivity, water content, and temperature (Del Grosso et al. 2000b). Gas diffusivity is a function of soil water content and soil physical properties.

Model Changes and Additions

The latest versions of DAYCENT (DAYCENT 4.5) and CENTURY (CENTURY 4.5) include several new features and model improvements. The most detailed changes are in the NPP submodels for trees and grasses/crops. In previous versions of the models the parameter controlling maximum plant growth rate was defined by the user for different vegetation types. Now, maximum potential plant growth rate is a function of solar radiation, which is calculated as a function of latitude and day of year. The models have the ability to simulate maintenance respiration of plant parts as a function of biomass and temperature, but this feature has not been tested. Grasses and crops are divided into two components, shoots and roots, while trees have five components; leaves, fine branches, large wood, fine roots, and coarse roots. C from NPP is now allocated dynamically among plant compartments as a function of phenology and nutrient/water stress. For all vegetation types below ground allocation increases as nutrient and water stress increase. C fixation occurs on a weekly basis in DAYCENT and on a monthly basis in CETURY. For annual grasses/crops a higher proportion of NPP is allocated below ground for seedlings.

DAYCENT and CENTURY simulate 3 types of trees, coniferous, drought deciduous and temperate deciduous. For all tree types except deciduous during the leaf out month, fine roots have 1st priority on fixed C, leaves have 2nd priority until optimum leaf area index is reached, and any remaining C is divided among fine branches, large wood, and coarse roots according to tree specific parameters. During the leaf out month for deciduous trees all of the fixed C is allocated to leaves. Leaf out and leaf drop months are a function of soil water content for drought deciduous trees and a function of day length and temperature for temperate deciduous trees.

The latest versions of CENTURY and DAYCENT include some additional improvements and features. The soil temperature affect on decomposition has been improved using new data that included a large number of measurements below 0 °C (Del Grosso et al., in prep.). Non-symbiotic soil N fixation is now a function of actual evapo-transpiration (AET) instead of precipitation. Soil reaction can evolve with time, i.e. the user can specify an initial and final pH value and soil pH will vary linearly based on the initial and final values. The models have a variable pH effect on decomposition depending on whether the substrate is decomposed primarily by fungi, bacteria, or both. Also, the latest version of DAYCENT can simulate a ground water table at the bottom of the soil profile. Water may not flow into the ground water table from above layers but can flow upwards from the water table via unsaturated flow. The user may specify that a portion of burned C (charcoal) flows to the passive SOC pool during fire events. Charcoal is resistant to decomposition and can form a significant proportion of total SOC in some ecosystems.

Model Validations

DAYCENT has been extensively tested using data collected from various global ecosystems. Models can be tested in a number of ways. One is to compare a model simulation with time series data for a single site. Another is to compare simulated and observed site or treatment average values for different treatments and sites. In this paper we use both approaches because the former shows how well the model can simulate seasonal variability driven by climate, plant phenology, and management events while the latter shows how well the model can distinguish differences driven by site specific variables such as soil type and vegetation cover.

Table 3.1 lists the sites used for the model validations reported in this paper. Land uses include grasslands, forests, dry land agriculture, and intensive agriculture. Ecosystem variables used for models tests include crop yields, SOC, N_2O emissions, CH_4 uptake, soil water content, and soil temperature. The general strategy used in the simulations for these sites is as follows. Climate, soil, vegetation, and land management data for each site were converted into DAYCENT input files required to run the model. Model pools were initialized by simulating at least 500 years of native vegetation appropriate for each site. DAYCENT land management files were adjusted to represent historical and modern lands use changes. For example, at Kellogg Biological Station (KBS) we simulated 2000 years of deciduous forest until 1880. From 1881 until the present we assumed that the land was under cultivation and modified crop rotations and fertilizer additions to represent the improvement of crop cultivars and increased fertilizer use that occurred during the 20^{th} century. Model output files for the years during which data were collected were compiled and observed and simulated mean values for the variables listed in Table 3.1 were calculated. An exception to this procedure is that some of the simulated CH_4 oxidation points were generated by running the CH_4 submodel using observed soil water content and temperature instead of the overall DAYCENT model.

Figure 3.1 shows simulated vs. observed average annual grain yields for the appropriate sites listed in Table 3.1. The model fit with the data is very good and there is little model bias. Both the model and data show high yields for corn and millet and lower yields for soybeans and wheat. DAYCENT also does a fairly good job simulating SOC but the scatter is higher than with grain yield and the highest observed SOC value was substantially under-estimated (Figure 3.2). Figure 3.3 shows a good correlation between simulated and observed CH_4 uptake but the model is biased in that sites with low CH_4 uptake tend to be over-estimated. The model shows general agreement with the data in that the highest CH_4 uptake rates are for deciduous forests and the lowest are for cropped systems while grasslands, coniferous, and tropical forests show intermediate CH_4 uptake. Model bias results mainly from a tendency to over-estimate CH_4 uptake from intensive agricultural systems. N_2O emissions were log transformed because the range of N_2O emissions across the reported data sets was large and sites with smaller fluxes over-lapped if non-transformed data was used. Again, the agreement between observed and simulated average values is favorable (Figure3. 4). Both the observations and DAYCENT show highest N_2O emission rates from intensive agriculture and lowest form grasslands with dryland agriculture and deciduous forest in between.

Figure 3.5 shows time series data for observed and simulated soil water content at the annual grassland at Jasper Ridge, CA. The model simulated the observed high soil water contents during winter and the dry down during the growing season quite well. DAYCENT also simulates seasonal fluctuations in soil temperature correctly as exemplified using data from winter wheat/fallow cropping in Nebraska (Figure 3.6).

Figure 3.7 has observed and simulated grain yields for the conventional till corn/soybean/winter wheat rotations at KBS. From 1989 until 1994 corn was grown on odd years and soybean during even years. Beginning in 1995, the rotation was changed to wheat/corn/soybean. The model shows very good agreement with the data. Figure 3.8 shows time series of observed and simulated N_2O emissions for the deciduous forest and the corn/soybean/winter wheat rotation at KBS from 1996-1998. The r^2 values calculated on a daily basis are not good but the model simulates most of the seasonal trends shown in the data. For example, the model and data show high emissions in June and low emissions in July during 1996 for both the deciduous forest and the cropped soil. Also, the model shows the high temporal variability shown in the data during the summer of 1998 in the cropped soils but the model often mistimes the pulses of N_2O emissions by a few days.

Discussion

This paper described changes in the DAYCENT ecosystem model and results of model validations. New features and additions to DAYCENT were intended to make the model more realistic, more versatile, and more mechanistic. Most of the changes were in the plant growth submodels. Important additions include dynamic C allocation among plant components, simulation of plant maintenance respiration, and making maximum potential plant growth rates vary with solar radiation. Users now have the options of simulating a soil water table, allowing soil pH to vary through time, and including charcoal in the recalcitrant SOC pool. All of the new features have been tested except simulated values for maintenance respiration have not been compared with any data.

Overall, DAYCENT compared favorably with the global data set used for these tests. The model can distinguish trends in plant growth, SOC, and trace gas fluxes associated with different types of vegetation cover and land use (Figures 3.1-3.4). Both the model and data showed higher SOC under no till for the KBS, MI and Sidney, NE sites. However, the model shows substantial error for a minority of sites. For example, N_2O emissions are under-estimated by a factor of ~2 for the organic agriculture treatments at KBS (Figure 3.3). The model simulates low N_2O emissions for the organic rotations because little or no fertilizer is added. These rotations include a winter leguminous cover crop. DAYCENT may not be simulating enough N fixation by the legumes, resulting in an underestimation of N_2O emissions.

The model does a good job simulating the observed time series for some, but not all variables. Soil water content and temperature were simulated well on a daily basis (Figures 3.5 and 3.6) but N_2O emissions show a weak correlation between observed and simulated values on the daily time scale (Figure 8). One reason for this is that the controls on soil water content (precipitation, soil physical properties, evapotranspiration) are simpler than the controls on N_2O emissions. N_2O emissions are driven by soil water content and other variables such as NH_4^+ and NO_3^- availability, soil redox potential, and microbial community. Given this complexity, it is encouraging that the model mimics the pattern of the observed N_2O flux data (high short term variability) although the day-to-day match with the data is faulty. These results are consistent with previous model tests showing that the fit between measured and simulated trace gas flux is poor on a daily basis but that the model shows the same general seasonal patterns as the data. Crop yields are simulated well when comparing averages across sites and when considering time series data within a site (Figures 3.1 and 3.7). This is related to grain yields being a cumulative state variable that is somewhat independent of short term variability in soil water content, N availability, and other driving variables.

Conclusions

These results show that a model of intermediate complexity can simulate some important ecosystem parameters quite well. DAYCENT is sensitive to site-specific factors that control average values of important ecosystem variables and can capture the seasonal variability exhibited within sites. Model weaknesses exposed by these tests include bias in the CH_4 uptake submodel and underestimation of N_2O emissions from organic agriculture. The model assumes that CH_4 uptake is inhibited in agricultural soils but the extent of this inhibition is apparently underestimated. These model tests are incomplete in that no alternative models were used as a reference. Comparisons between DAYCENT and alternative ecosystem models are in progress and plans are being made to use gas flux tower data to test the maintenance respiration submodel.

References

Borken, W., *Methan-Aufnahme und Kohlendioxid-Freisetzung von Waldboeden*, Ph.D. Dissertation, Univ. of Göttingen, Göttingen, Germany, 1996.

Clayton, H., McTaggert, I.P., Parket, J., Swan,.L. & Smith, K.A. 1997. Nitrous oxide emission from fertilized grassland: a two year study of the effect of N fertilizer form and environmental conditions. *Biol. Fert. Soils 25*: 252-260.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Holland, E.A., Pendall, E., D.S. Schimel, D.S. & Ojima, D.S. Modeling CO_2 Emissions from Decomposition of Soil Organic Carbon. In prep.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Kulmala, A.E. & Phongpan, S. 2000a. General model for N_2O and N_2 gas emissions from soils due to denitrification. *Global Biogeochemical Cycles 14*: 1045-1060.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Potter,C.S., Borken, W., Brumme, R., Butterbach-Bahl, K., Crill, P.M., Dobbie, K. & Smith, K.A. 2000b. General CH_4 oxidation model and comparisons of CH_4 oxidation in natural and managed systems. *Global Biogeochemical Cycles 14*: 999-1019.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S. & Schimel, D.S. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In M. Schaffer, L. Ma, & S. Hansen (eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*: 303-332. Boca Raton, Florida: CRC Press.

Dobbie, K.E., and K.A. Smith, Comparison of CH_4 oxidation rates in woodland, arable and set aside soils, *Soil Biol. Biochem.*, *28*, 1357-1365, 1996.

Dong, Y., D. Scharffe, J.M. Lobert, P.J. Crutzen, and E. Sanhueza, Fluxes of CO_2, CH_4 and N_2O from a temperate forest soil: The effects of leaves and humus layers, *Tellus, Ser. B*, *50B*, 243-252, 1998.

Eitzinger, J., Parton, W.J., Hartman, M.D., 2000. Improvement and validation of a daily soil temperature submodel for freezing/thawing periods. Soil Science 165, 525-534.

Flessa, H., P. Dörsch, and F. Beese, Seasonal variation of N_2O and CH_4 fluxes in differently managed arable soils in southern Germany, *J. Geophys. Res.*, *100*, 23,115-23,124, 1995.

Goldman, M.B., P.M. Groffman, R.V. Pouyat, M.J. McDonnell, and S.T. Pickett, CH_4 uptake and N availability in forest soils along an urban to rural gradient, *Soil Biol. Biochem.*, 27, 281-286, 1995.

Kelly, R.H., Parton, W.J., Hartman, M.D., Stretch, L.K., Ojima D.S. & Schimel, D.S. 2000. Intra and interannual variability of ecosystem processes in shortgrass steppe. *Journal of Geophysical Research: Atmospheres 10:* 20,093-20,100.

Kessavalou, A., Mosier, A.R., Doran, J.W., Drijber, R.A., Lyon, D.L. & Heinemeyer, O. 1998. Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. *Journal of Environmental Quality 27*: 1094-1104.

Keller, M., E. Veldkamp, A.M. Weltz, and W.A. Reiners, Effect of pasture age on soil trace gas emissions from a deforested area of Costa Rica, *Nature*, *365*, 244-246, 1993.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton, W.J. 1993, *CENTURY soil organic matter model environment, Technical documentation, Agroecosystem version 4.0.* Fort Collins, CO: Colorado State University.

Mosier, A.R., W.D. Guenzi, and E.E. Schweizer. 1986. Soil losses of dinitrogen and nitrous oxide from irrigated crops in northeastern Colorado. Soil Sci. Soc. Am. J. 50:344-348.

Mosier, A.R., L.K. Klemedttson, R.A. Sommerfeld, and R.C. Musselman, Methane and nitrous oxide flux in a Wyoming subalpine meadow, *Global Biogeochem. Cycles, 7,* 771-784, 1993.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel, and J.A. Delgado, CH_4 and N_2O fluxes in the Colorado shortgrass steppe, 1, Impact of landscape and nitrogen addition, *Global Biogeochem. Cycles, 10,* 387-399, 1996.

Mosier, A.R., and J.A. Delgado, Methane and nitrous oxide fluxes in western Puerto Rica, *Chemosphere, 9,* 2059-2082, 1997.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel, and O. Hienemeyer, CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change, *Global Biogeochem. Cycles, 11,* 29-42, 1997.

Parton, W.J., Ojima, D.S., Cole C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In, *Quantitative Modeling of Soil Forming Processes*: 147-167. Madison, WI: Soil Science Society of America.

Parton, W.J., A.R. Mosier, D.S. Ojima, D.W. Valentine, D.S. Schimel, K. Weier, and K.E. Kulmala, 1996, Generalized model for N_2 and N_2O production from nitrification and denitrification, *Global Biogeochemical Cycles, 10,* 401-412.

Parton, W.J., Hartman, M.D., Ojima, D.S. & Schimel, D.S. 1998. DAYCENT: Its land surface submodel: description and testing. *Global Planetary Change 19*: 35-48.

Parton, W.J., Holland, E.A., Del Grosso, S.J., Hartman, M.D., Martin, R.E., Mosier, A.R., Ojima, D.S., Schimel, D.S. 2001. Generalized model for NO_x and N_2O emissions from soils. *Journal of Geophysical Research 106 (D15)*: 17403-17420.

Peterson, G.A., Westfall, D.D., Peairs, F.B., Sherrod, L., Poss, D., Gangloff, W., Larson, K., Thompson, D.L., Ahuja, L.R., Koch, M.D., Walker, C.B., 2000. Sustainable dryland agroecosystem management, TB00-03. Colorado State University and Agricultural Experiment Station, Fort Collins, CO.

Robertson, GP, Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 1922-1925.

Steudler, P.A., J.M. Mellilo, B.J. Feigl, C. Neill, M.C. Piccolo, and C.C. Cerri , Consequence of forest to pasture conversion on CH_4 fluxes in the Amazon basin, *J. Geophys. Res.*, *101*, 18,547-18,554, 1996.

Table 3.1 Summary of the data used to test DAYCENT

Site	Vegetation	Land use	Variables	Source
Sidney, NE	wheat/fallow	conv till	SOC, N_2O, soil temp	Kessavalou et al., 1998
Sidney, NE	wheat/fallow	no till	SOC, N_2O	Kessavalou et al., 1998
Sidney, NE	grass	grazing	SOC, N_2O	Kessavalou et al., 1998
Sterling, CO	wheat/fallow	no till	SOC, grain	Peterson et al., 2000
Sterling, CO	annual cropping	no till	SOC, grain	Peterson et al., 2000
Sterling, CO	grass	grazing	SOC, grain	Peterson et al., 2000
CPER, CO***	shortgrass	grazed	CH_4	Mosier et al., 1996
Fort Collins, CO	Wheat/fallow	Conv till	N_2O, CH_4	Mosier et al., 1997
Fort Collins, CO	corn/barley	conv till	N_2O, CH_4	Mosier et al., 1986
Jasper Ridge, CA	Annual grassland		Soil water	R. Shaw pers. comm.
KBS, MI*	deciduous forest		SOC, grain, N_2O, CH_4	Robertson et al., 2000
KBS, MI*	corn/soy/wheat	conv till, high N	SOC, grain, N_2O, CH_4	Robertson et al., 2000
KBS, MI*	corn/soy/wheat	no till high N	SOC, grain, N_2O, CH_4	Robertson et al., 2000
KBS, MI*	corn/soy/wheat	conv till low N	SOC, grain, N_2O, CH_4	Robertson et al., 2000
KBS, MI*	corn/soy/wheat	conv till no N	SOC, grain, N_2O, CH_4	Robertson et al., 2000
Wyoming	coniferous forest		CH_4	Mosier et al., 1993
New York	deciduous forest		CH_4	Goldman et al., 1995
Brazil	tropical forest		CH_4	Steudler et al, 1996
Costa Rica	tropical forest		CH_4	Keller et al., 1993
Swift Current, SA	wheat	conv till	grain	pers. comm.
Germany	Intensive agriculture	conv till	N_2O, CH_4	Flessa et al., 1995
Germany	coniferous		CH_4	Borken, 1996
Germany	deciduous forest		CH_4	Dong et al., 1998
Germany	deciduous forest		CH_4	K. Butterbach-Bahl (unpublished data, 1995)
Puerto Rico	grassland		CH_4	Mosier and Delgado, 1997
Puerto Rico	grassland	fertilized	CH_4	Mosier and Delgado, 1997
Scotland	grass	former agricultural	CH_4	Dobbie and Smith, 1996
Scotland	wheat	agricultural	CH_4	Dobbie and Smith, 1996
Scotland	rye	fertilized	N_2O	Clayton et al., 1997

* = Kellogg Biological Station, Michigan
** = Central Experimental Farm, Ottawa, Ontario
*** = Central Plains Experimental Range, Colorado

List of Figures

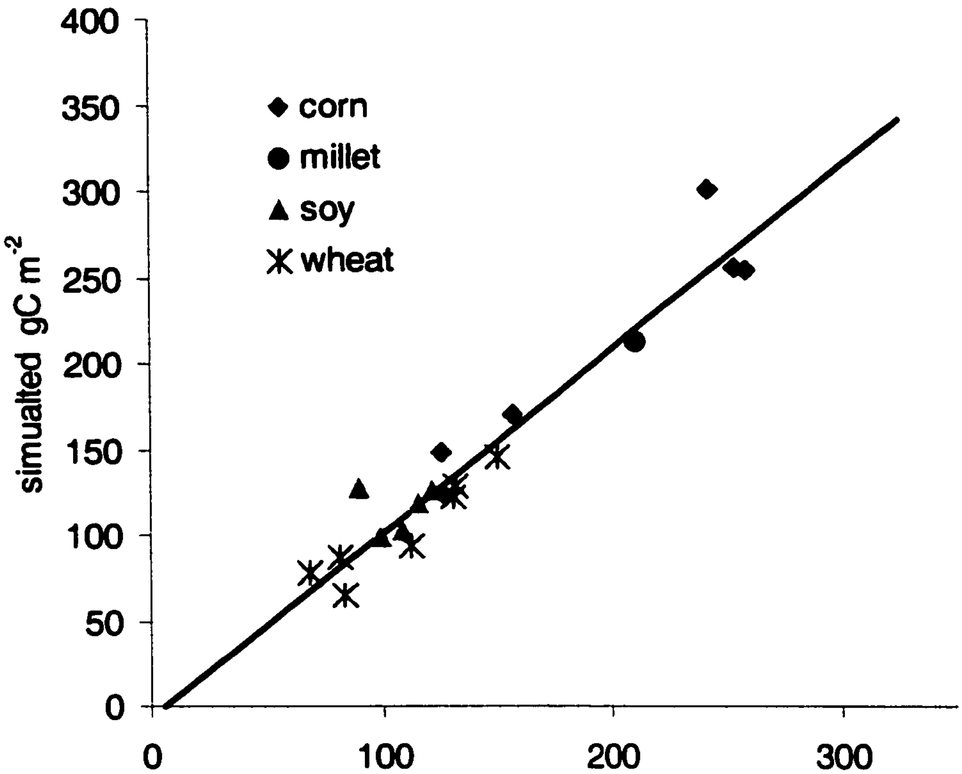


Figure 3.1

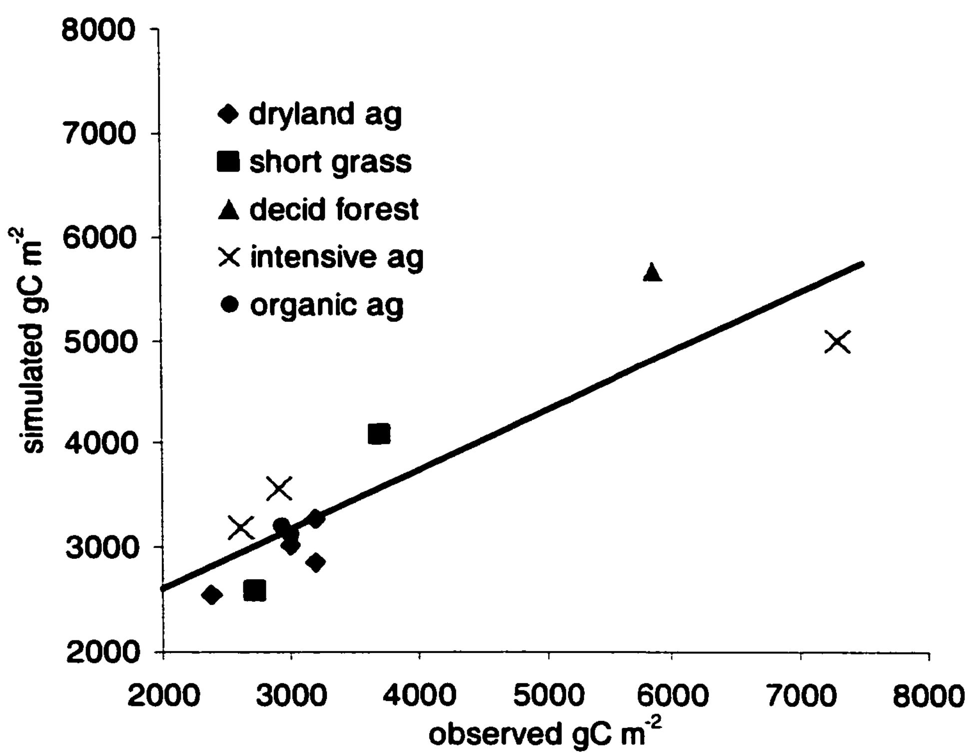


Figure 3.2

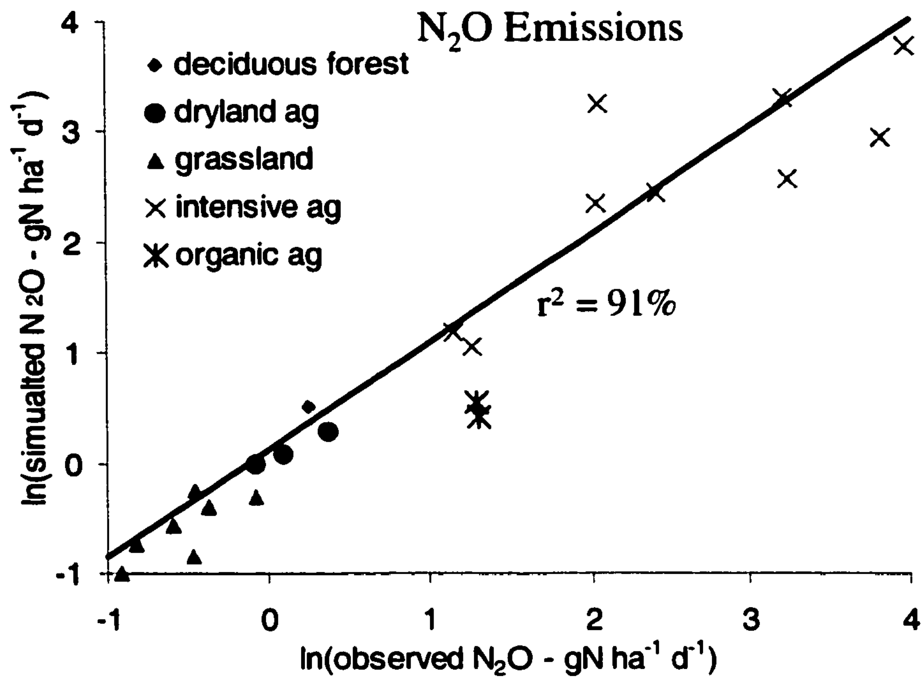


Figure 3.3

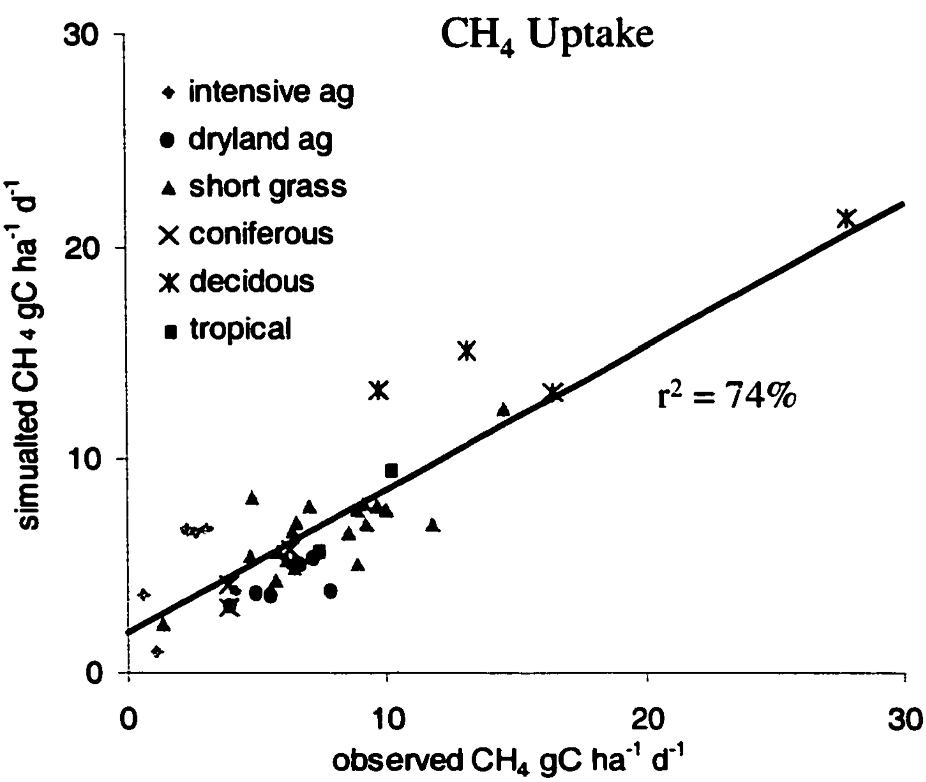


Figure 3.4

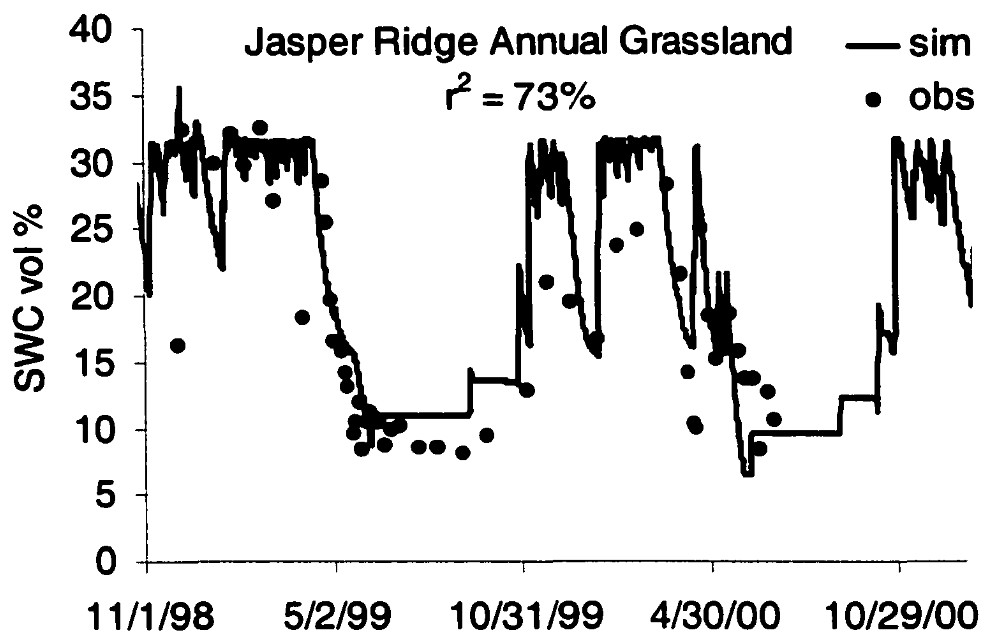


Figure 3.5

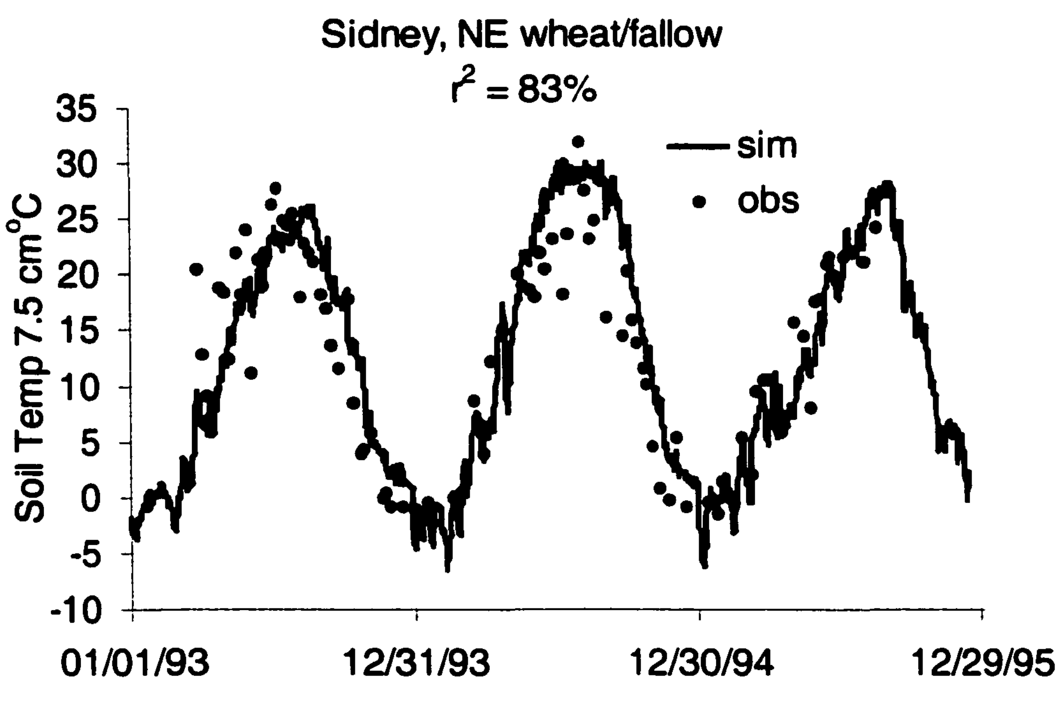


Figure 3.6

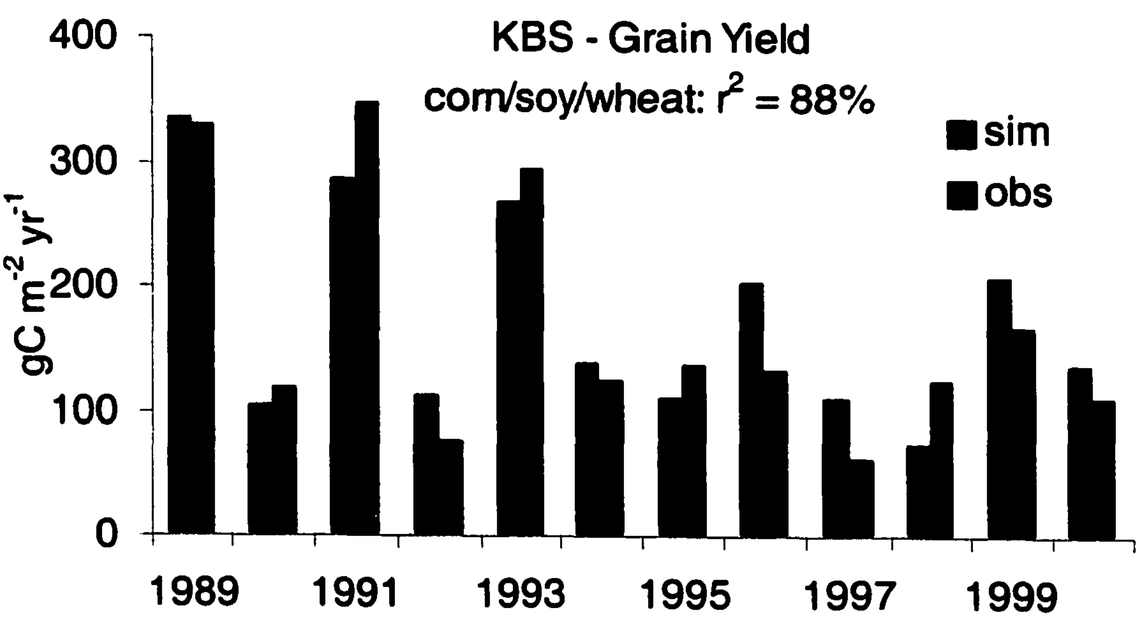

KBS - Grain Yield
corn/soy/wheat: r2 = 88%
sim
obs
400
300
200
100
0
gC m-2 yr-1
1989
1991
1993
1995
1997
1999

Figure 3.7

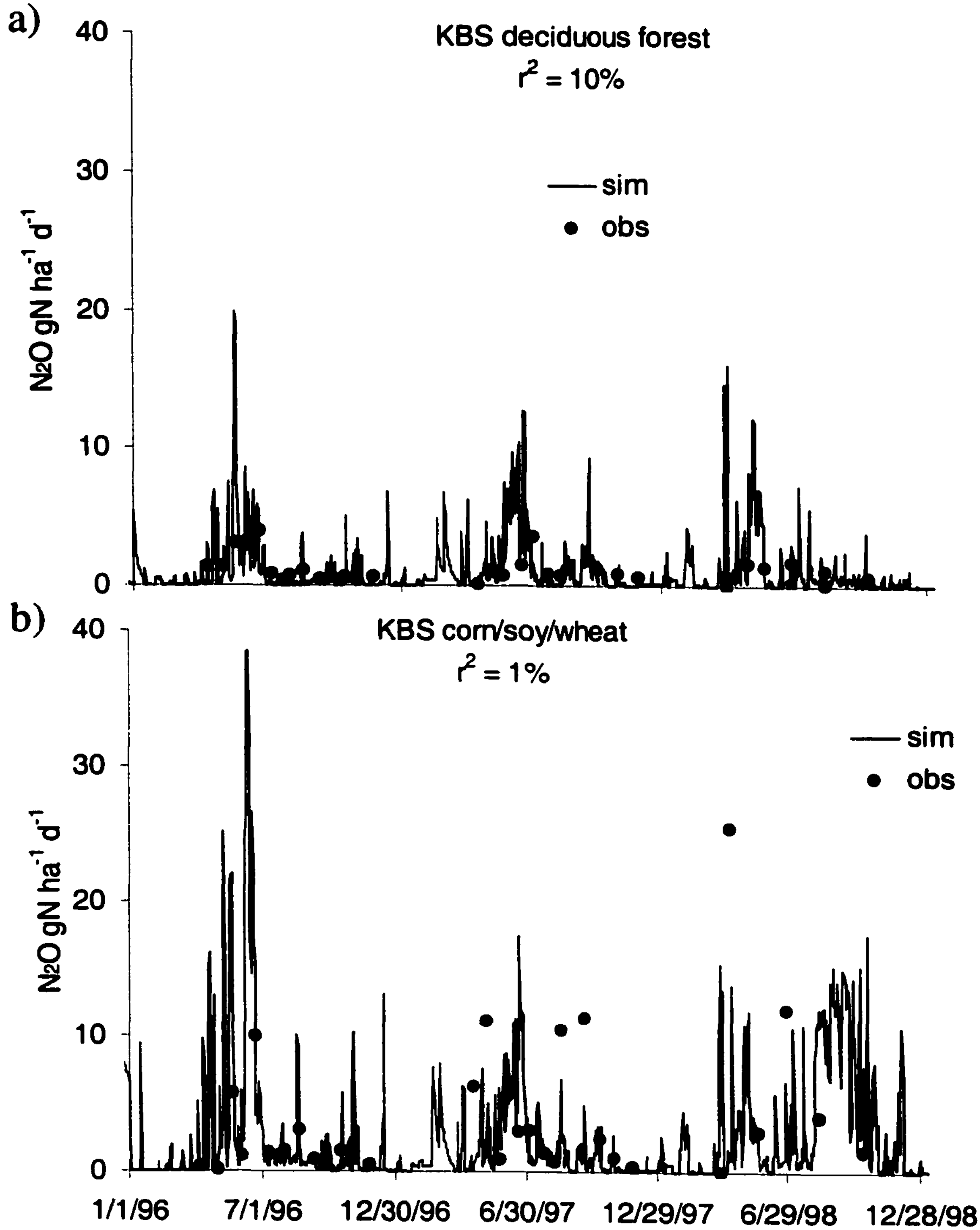

a)
KBS deciduous forest
r^2 = 10%
sim
obs
N2O gN ha-1 d-1
40
30
20
10
0
b)
KBS corn/soy/wheat
r^2 = 1%
sim
obs
N2O gN ha-1 d-1
40
30
20
10
0
1/1/96
7/1/96
12/30/96
6/30/97
12/29/97
6/29/98
12/28/98

Figure 3.8

CHAPTER 4

SIMULATED EFFECTS OF LAND USE, SOIL TEXTURE, AND PRECIPITATION ON N GAS EMISSIONS USING DAYCENT

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Keough, C.A., Peterson, G.A., Ojima, D.S., Schimel, D.S., 2001. Simulated effects of land use, soil texture, and precipitation on N gas emissions using DAYCENT. In: Follett, R.F., Hatfield, J.L. (Eds.), *Nitrogen in the Environment: Sources, Problems, and Management*, p. 413-431. Elsevier Science Publishers, The Netherlands.

Abstract

We describe the N gas (N_2O, NO_x, N_2) flux submodel used in the DAYCENT ecosystem model and demonstrate the ability of DAYCENT to simulate the low N gas emissions observed from native soils, the intermediate emissions associated with dryland agriculture, and the high emissions observed for irrigated agricultural soils. Although DAYCENT did not always capture the observed daily variability in N gas emissions, it did simulate the observed seasonal patterns of N gas emissions within systems and differences in mean emissions among systems reasonably well. DAYCENT was used to compare N gas emissions from soils for native range grass, winter wheat/fallow conventional till and no till, winter wheat/corn/fallow no till, irrigated corn and irrigated silage cropping. NO_x made up the majority of N gas fluxes in all cases followed by N_2O (2-21% of N gas fluxes) and N_2 (0.1-11% of N gas fluxes). Yearly N_2O emissions ranged from 0.06-0.1 kgN ha^{-1} yr^{-1} for native range grass, 0.25-0.67 kgN ha^{-1} yr^{-1} for winter

wheat/fallow and silage cropping, and 1-1.5 kgN ha^{-1} yr^{-1} for the irrigated corn. NO_x emissions declined while N_2O and N_2 emissions increased as soil texture became finer. Soil water inputs, tillage, timing of crop/fallow periods and fertilizer application interact to control N gas emissions so generalizations regarding land use are difficult to make. Switching to no till without changing the winter wheat/fallow cropping schedule resulted in higher N_2O emissions because the increased soil water content induced by no till supported higher denitrification rates. However, the soil water savings associated with no till also allows a reduction in the fallow period and the 3-year winter wheat/corn/fallow rotations had lower N_2O and NO_x emissions than the 2-year winter wheat/fallow systems considered.

Introduction

Flows of nitrogen (N) between the atmosphere, soil, and biota strongly influence the carbon (C) cycle and atmospheric chemistry. Net primary productivity (NPP) is limited by N availability in most terrestrial ecosystems (Vitousek and Howarth, 1991; Levin, 1989) and N transformations in soils are a major source of N gas emissions to the atmosphere (Davidson and Kingerlee, 1997; Kroeze et al., 1999). Nitrous oxide (N_2O) is a long lived, important greenhouse gas (Prather et al., 1995). Nitric oxide (NO) and its oxidized counter part, NO_2, (together referred to as NO_x) are major ozone regulators and limit the overall oxidizing capacity of the troposphere (Williams et al., 1992). Human activity has profoundly altered fixation rates of atmospheric N_2 and emission rates of N_2O and NO_x to the atmosphere. The amount of reactive N induced into the biosphere from fertilizer production, N-fixation in crops and fossil fuel combustion exceeds the N fixed annually in natural systems (Smil, 1999; Vitousek et al., 1997; Galloway et al., 1995). Anthropogenic activities, mainly fossil fuel burning and agriculture, are major sources of atmospheric NO_x (Prather et al., 1995) while biogenic processes are the major source of N_2O (Kroeze et al., 1999).

The atmospheric concentration of N_2O has been well documented for current and historical time periods (Prather et al., 1995). In contrast, the amount of N in soils and the biota, as well as the flows of N that contribute to the observed changes in atmospheric N_2O, cannot be measured directly on the global scale. Ecosystem models are necessary to scale up results of plot sized experiments and calculate the contributions of natural and managed systems to global N budgets. Simple empirical models correlate N gas flux with N additions (IPCC, 1997) or with soil water content (Davidson and Verchot, 2000). At the opposite extreme, highly mechanistic models explicitly simulate the biological, physical, and chemical processes involved in N transformations and flows (Grant and Pattey, 1999). Simple models tend to be over-generalized and cannot represent the heterogeneity of real world systems while mechanistic models require detailed parameterization and intensive computation. DAYCENT is an ecosystem model of intermediate complexity, some processes are represented mechanistically but the model requires a relatively small number of site specific parameters. In this chapter we begin with a brief overview of the DAYCENT model and describe the N gas submodel of DAYCENT in detail. Then we present comparisons of simulated and observed values of N gas emissions to demonstrate the validity of DAYCENT. Lastly, we use DAYCENT to compare annual N gas (NO_x, N_2O and N_2) emissions associated with different land uses, soil textures, and weather data.

DAYCENT Model Description

DAYCENT (Kelly et al., 2000; Parton et al., 1998; Del Grosso et al., 2001) is the daily time step version of the CENTURY model. CENTURY (Parton et al., 1994) operates on a monthly time step and was developed to simulate changes in soil organic matter (SOM), plant productivity, nutrient availability and other ecosystem parameters in response to changes in land management and climate. However, finer time scale resolution is required to simulate N gas emissions from soils because the processes that result in N gas fluxes respond nonlinearly to important controls such as soil water content. DAYCENT simulates exchanges of carbon, nutrients, and trace gases among the atmosphere, soil, and plants as well as events and management practices such as fire, grazing, cultivation, and organic matter or fertilizer additions. To run DAYCENT for a particular site, soil texture, current and historical land use, and daily maximum/minimum temperature and precipitation data are required. Soil water content, temperature, mineral N concentration, trace gas flux, and SOM decomposition are simulated on a daily time step while plant growth is updated weekly.

DAYCENT (Figure 4.1) includes submodels for plant productivity, decomposition of dead plant material and SOM, soil water and temperature dynamics, and N gas fluxes. Flows of C and nutrients are controlled by the amount of C in the various pools, the N concentrations of the pools, abiotic temperature/soil water factors, and soil physical properties related to texture. Net Primary Productivity (NPP) is a function of nutrient availability, soil water and temperature, shading, and vegetation type (Metherell et al., 1993). NPP is divided among leafy, woody, and root compartments based on plant type. The root to shoot ratio of NPP allocation is a function of soil water content and mineral N availability. The death rate of plant compartments is controlled by soil water, temperature, season, and plant specific senescence parameters. Structural detritus has a higher C:N ratio and is more difficult to decompose than metabolic detritus. SOM is divided into three pools based on decomposition rates (Parton et al., 1993; 1994). Decomposed detrital material that has a low C:N ratio flows to the active SOM pool, which includes microbial biomass and the highly labile by-products of decomposition that turnover in approximately one year or less. The products of detrital decomposition that have a wider C:N ratio flow to the slow SOM pool, which includes the relatively resistant (10-50 year turnover rate) by-products of decomposition. The passive SOM pool consists of humus that is extremely resistant to further decomposition. As soils become finer textured a lower portion of SOM is respired as CO_2 and more SOM is retained in stable form due to physical and chemical protection. Decomposition of SOM and external nutrient additions supply the nutrient pool, which is available for plant growth and microbial processes that result in trace gas fluxes. Ammonium (NH_4^+) is modeled for the top 15 cm while nitrate (NO_3^-) is distributed throughout the soil profile. Nutrients and SOM are concentrated near the soil surface and decrease exponentially with depth. The land surface submodel of DAYCENT simulates water flow through the plant canopy, litter and soil profile, as well as soil temperature throughout the profile (Parton et al., 1998; Eitzinger et al., in press). DAYCENT has been shown to reliably model soil water content, N mineralization, and NPP for a shortgrass steppe in Colorado (Kelly et al., 2000). The SOM and N cycling submodels used in DAYCENT have been validated for various systems including grasslands and forests (Kelly et al., 1997), as well as agricultural soils in Sweden (Paustian et al., 1992) and Oregon (Parton and Rasmussen, 1994).

The N gas submodel of DAYCENT (Figure 4.2) simulates soil N_2O and NO_x gas emissions from nitrification and denitrification as well as N_2 emissions from denitrification. Nitrifying microbes oxidize NH_4^+ to NO_3^-, with some N_2O and NO_x released during the intermediate steps. N gas flux from nitrification is assumed to be a function of soil NH_4^+ concentration, water content, temperature, and pH (Parton et al., 1996; Paron et al., in press). Nitrification rates increase linearly with soil NH_4^+ concentration. Nitrification is limited by moisture stress on biological activity when soil water-filled pore space (WFPS = % relative saturation) is too low and by O_2 availability when WFPS is too high. Nitrification increases exponentially with temperature and stabilizes when soil temperature exceeds the site specific average high temperature for the warmest month of the year. Nitrification is not limited when pH is greater than neutral but decreases exponentially as soils become acidic.

Denitrification is an anaerobic process in which heterotrophic microbes reduce NO_3^- to NO_x, N_2O, and N_2. Denitrification is a function of soil NO_3^- (e^- acceptor) concentration, labile C (e^- donor) availability, WFPS, and soil physical properties related to texture that influence gas diffusivity (Parton et al., 1996; Del Grosso et al., 2000a). Denitrification increases exponentially with increasing soil NO_3^- concentration when NO_3^- concentration is low (< 50 ppm) and approximately linearly at higher NO_3^- levels. Denitrification increases approximately linearly with soil heterotrophic respiration, a proxy for labile C availability. No denitrification is assumed to occur until WFPS values exceed 50-60%, then denitrification increases exponentially until WFPS reaches 70-80%

and it stabilizes as soil water content approaches saturation. The model calculates N_2 + N_2O emissions from denitrification by assuming that the process is controlled by the input (NO_3^-, respiration, WFPS) that is most limiting. N_2O emissions are calculated from N_2 + N_2O gas emissions and an N_2:N_2O ratio function. The ratio of N_2:N_2O gases emitted due to denitrification is assumed to increase as the ratio of e^- acceptor (NO_3^-) to e^- donor (labile C) decreases and as soil gas diffusivity and O_2 availability decrease. N_2O can act as an alternative e^- acceptor and be reduced to N_2 when labile C is in excess compared to NO_3^-. D/D_o, a relative index of gas diffusivity in soils, is calculated as a function of WFPS and soil physical properties (bulk density and field capacity) that influence gas diffusion rates using equations presented by Potter et al. (1996). As D/D_o decreases, the residence time of N_2O in soil increases, thus increasing the probability that N_2O will be further reduced to N_2 before diffusing from the soil.

NO_x emissions from soil are a function of total N_2O emissions, a NO_x/N_2O ratio equation, and a precipitation initiated pulse multiplier (Parton et al., submitted). Simulated N_2O gas emissions from nitrification and denitrification are summed to obtain total N_2O flux. The NO_x/N_2O ratio is high (maximum of ~20) when D/D_o is high and decreases to a minimum of ~1 as D/D_o decreases. This is based on the following observations. The majority of NO_x emissions from soils are from nitrification because NO_x is highly reactive under the reducing conditions that facilitate denitrification (Conrad, 1996). Total N gas flux is due primarily to nitrification when soils are well aerated (high D/D_o) and mainly to denitrification under anaerobic conditions (Davidson, 1993; Linn and Doran, 1984). Thus, the model assumes that NO_x becomes a larger proportion of total N gas emissions as soil gas diffusivity increases. The modeled total

N_2O emission rate is multiplied by the ratio function to obtain a base NO_x emission rate. The base NO_x emission rate may be modified by a pulse multiplier. Large pulses of NO_x are often initiated when precipitation falls on soils that were previously dry (Smart et al., 1999; Martin et al., 1998; Hutchinson et al., 1993). The pulses are thought to be related to substrate accumulation and activation of water stressed bacteria upon wetting (Davidson, 1992). To account for these pulses the model incorporates the pulse multiplier submodel described by Yienger and Levy (1995). The magnitude of the multiplier is proportional to the amount of precipitation and the number of days since the latest precipitation event, with a maximum multiplier of 15.

On a daily time step simulated values of soil NH_4^+, NO_3^-, heterotrophic CO_2 respiration, water content, temperature and site specific values for soil texture and physical properties are used to calculate N_2O emissions from nitrification and denitrification and N_2 emissions from denitrification. Total N_2O emissions, a NO_x/N_2O ratio function, and a pulse multiplier are used to calculate NO_x emissions. N balance is verified on a daily basis and calculated potential N gas emission rates are revised downwards if there is not enough NO_3^- and NH_4^+ available to supply the potential N gas emissions for a particular time step.

DAYCENT Model Validation

We first summarize results of previous tests of the DAYCENT model for various natural and managed systems then present results of tests with an updated version of the model on soils used for winter wheat/fallow cropping. Frolking et al. (1998) compared simulated and observed values of soil water content, mineral N, and N_2O emissions for soils in Colorado, Scotland, and Germany. The Colorado site is a dry shortgrass steppe (annual ppt. ~36 cm), the Scotland site is a fairly moist ryegrass pasture (annual ppt. ~85 cm), and the German sites are perennially cropped (annual ppt. ~83 cm). DAYCENT correctly simulated the observed low N_2O fluxes for the shortgrass steppe, the moderate N_2O emissions for the Scotland site and the high N_2O emissions observed for the cropped soils. DAYCENT also simulated the observed daily variability in N_2O emission rates and soil water content reasonably well for the different sites. Parton et al. (in press) tested DAYCENT simulations of soil water content, soil temperature, and N_2O and NO_x gas emissions from rangeland soils of varying texture and fertility levels. DAYCENT simulated soil temperature, WFPS, and NO_x emissions generally well on daily and seasonal bases, although winter season WFPS values were not well represented. DAYCENT did not accurately represent the observed daily variability in N_2O emissions. However, DAYCENT simulated the observed seasonality of N_2O emissions fairly well, although winter season N_2O emissions tended to be underestimated. Del Grosso et al. (2001) tested the ability of DAYCENT to simulate soil water, temperature, NH_4^+, NO_3^-, and N_2O emissions for irrigated, fertilized barley (*Hordeum vulgare*) and corn (*Zea mays*) crops. Similar to the rangeland soils, soil temperature and water were generally simulated rather well, but winter season WFPS values were not accurately represented by the model. DAYCENT correctly simulated high values of NH_4^+ and NO_3^- after fertilization in spring and decreasing values during the growing season. Simulated values of N_2O emissions compared favorably with the data for the corn crop, but N_2O emissions were overestimated for the barley crop.

The latest version of DAYCENT was tested with N_2O gas flux data collected from winter wheat/fallow fields during 1992-1995 (Mosier et al., 1997). The fields are on private land in northeastern Colorado and had been used for winter wheat/fallow cropping for over 60 years. We tested DAYCENT with data from two fields, one (WE) had been planted with winter wheat in September of even years and the other (WW) had been planted with winter wheat in September of odd years. Both fields are classified as sandy loams and were fertilized with sewage sludge during the fallow season starting in 1990. Herbicides were used to control weeds and conventional tillage cultivation was used. Figure 4.3 shows a time series of simulated and observed N_2O fluxes for each field. The day to day variability in N_2O flux is very high, but DAYCENT correctly simulated the observed patterns of N_2O flux fairly well. Although some individual points are greatly over or under estimated, the model correctly simulated many of the observed high N_2O fluxes associated with snow melt events during the spring as well as some of the high N_2O fluxes observed during the summer. The model often mistimes the large N_2O flux events by a few days but this may be at least partially due to differences between the precipitation data used to drive the model and the precipitation that fell on the fields. The model was driven with weather data from the Central Plains Experimental Range (CPER) which is ~20 km from the winter wheat/fallow fields. Comparisons of average simulated and observed annual N_2O emissions for the winter wheat/fallow fields and soils under alternative land uses that were tested show that the model does well in most cases (Figure 4.4). The barley field was fertilized at the same level as the corn field and the spring the barley was planted was relatively wet (Mosier et al., 1986) but the simulated high N_2O emissions due to denitrification episodes were not observed. A possible explanation is that growth patterns of the barley affect N availability for microbial processes that result in N_2O gas emissions.

Results of tests with many soils show that the DAYCENT model does not always reliably simulate the observed daily variability in N_2O fluxes but does accurately simulate differences in N_2O fluxes between different sites and among seasons for a given site. Difficulties in modeling soil water content in winter and spring are responsible for some of the errors in simulated N_2O emission rates. WFPS is an important driver of the processes that control N_2O emission rates but heterogeneity in snow drifting and snow melting make it difficult to simulate soil WFPS during winter and spring. This variability of important model drivers on smaller scales than are resolved by the model contributes to the observed model error. The ability of DAYCENT to reliably simulate NO_x emissions has not been extensively tested but Parton et al. (in press) showed that the model represented the observed monthly patterns of NO_x flux and captured the observed differences in average NO_x flux from rangeland soils of varying texture and fertility levels. The ability of DAYCENT to simulate N_2 emissions has not been extensively validated because little field data for N_2 emissions exist. However, the denitrification submodel reliably modeled (r^2=0.47) daily N_2+N_2O emissions from agricultural soils in Pakistan (Del Grosso et al., 2000a).

DAYCENT Model Application

The effects of land use, soil texture, and precipitation on N gas emissions from soils in the U.S. Great Plains were compared using the DAYCENT model. The U.S. Great Plains is a semi-arid region with annual precipitation ranging from 30-60 cm. The winter wheat/fallow cropping system has been used extensively in the Great Plains because soil water stored during the fallow season leads to higher water availability during the cropped season. However, this system has led to a 50% decrease in soil organic matter (SOM) after 30-50 years (Peterson et al., 1998). Alternatives to winter wheat/fallow cropping have been proposed which store C in SOM depleted soil and compensate for CO_2 gas emissions (Bruce et al., 1999; Lal et al., 1998). However, the greenhouse effects of N_2O emissions must also be included in calculations of net greenhouse gas exchanges between the atmosphere and the soil (Del Grosso et al., 2000b; Robertson et al., 2000). NO_x budgets are important because NO_x affects the oxidizing capacity of the troposphere. From an N balance perspective it is desirable to account for total N gas (N_2O, NO_x and N_2) emissions from soils. We performed DAYCENT simulations and compiled annual N_2O, NO_x and N_2 emissions from soils of different texture, moisture, and cropping scenarios. We used weather data from the Central Plains Experimental Range (CPER) in northern Colorado (ann. ppt. ~35 cm, ann. temp. ~9.5 ^{o}C) to simulate N gas emissions from sandy loam, loam, and clay loam soils used for conventional winter wheat/fallow, no till winter wheat/fallow, irrigated corn, irrigated silage, and native range grass. Weather data from Sterling, Colorado (ann. ppt. ~40 cm, ann. temp. ~9.7 ^{o}C) were used to compare N gas emissions from a loam soil under winter wheat/fallow conventional tillage, winter wheat/fallow no till, and winter wheat/corn/fallow rotations under no till. Land use alternatives are summarized in Table 4.1.

Winter wheat/fallow rotations were simulated by planting in September, harvesting the following July, and leaving the field fallow from August of the harvest year through August of the following year. Corn and silage were planted in May and harvested in September. To simulate winter wheat/corn/fallow rotations, winter wheat was planted in September of the 1st year and harvested the following July. The field was left fallow until the following year when dryland corn was planted in May and harvested in October. The field was left fallow after the corn harvest until winter wheat was planted again the following September.

Before simulating the different land use scenarios, SOM and mineral N (NH_4^+, NO_3^-) pools were initialized for the different soils by running the model for 75 years of winter wheat/fallow cropping under conventional tillage using the respective weather files and soil parameters. The various land use scenarios were simulated for 50 years and average annual N_2O, NO_x and N_2 emission rates were calculated.

To illustrate the inter-annual variability in N gas emissions, Figure 4.5 shows 15-year time series of NO_x and N_2O emissions for the three management alternatives along with precipitation data from the Sterling weather file. The winter wheat/fallow rotations had high N gas emissions during the fallow year and low emissions during the planted year. The no till winter wheat/fallow option had the highest NO_x and N_2O emissions during most years but some years show emissions from the other two scenarios that equal or exceed those from the no till winter wheat/fallow. The 3-year winter wheat/corn/fallow rotation is less variable because fallow periods during the summer months are reduced. In addition to the timing of crop/fallow seasons, variability is driven by interactions involving the timing of planting, harvesting, tillage, N addition and climate patterns. 1990 had very high N gas emissions from the winter wheat/fallow no till because it was fallow during the summer of that year and precipitation was high. The emissions for the winter wheat/corn/fallow alternative were low in 1990 because corn was growing during the summer of that year so less N was available for nitrification and denitrification. To isolate the effects of land use, soil texture, and precipitation, we averaged N gas emissions from 50-year simulations of each scenario.

Average annual N gas emission rates for the sandy loam, loam, and clay loam soils driven with the CPER weather data were highest for the irrigated corn and lowest for the native range grass (Figure 4.6a). NO_x emissions were strongly affected by texture with decreasing sand content associated with decreasing NO_x emissions (Figure 4.6b). N_2O emissions were highest for the corn, lowest for the range grass, and increased as sand content decreased (Figure 4.6c). N_2 emissions were highest for the corn and tended to increase as sand content decreased (Figure 4.6d). The majority of total N gas emissions from soil were in the form of NO_x. N_2O emissions were responsible for 2 to 21% of the total N gas fluxes. N_2 emissions represented a low proportion of the total N gas emissions in most cases (0.1 - 11%) and were highest for the corn grown in clay loam soil (Figure 4.6d). We must point out that these results are based on calculations of soil N gas emissions and that ecosystem losses of N due to NO_x emissions are likely to be much lower because 50% or more of soil NO_x emissions may be absorbed by the plant canopy (Yienger and Levy, 1995).

Figures 4.6e and 4.6f show the ratios of NO_x/N_2O and N_2/N_2O gases emitted for the various scenarios considered. Average NO_x/N_2O ratios were always greater than one and decreased as soil texture became finer. Finer soil texture is associated with lower gas diffusivity and higher water retention which favor the anaerobic conditions that facilitate reduction of NO_x to N_2O. The ratio of N_2/N_2O gases emitted was always less than one for the simulations performed. It should be noted that the ratio of N_2/N_2O gases emitted from denitrification is usually greater than one but figures 6e and 6f include N_2O fluxes from nitrification and denitrification. The ratio of N_2/N_2O gases tended to increase as clay content increased because the anoxic conditions that favor the reduction of N_2O to N_2 are more prevalent in finer textured soils.

The corn had the highest N gas emissions because it was fertilized and irrigated. Fertilization supplies labile N and irrigation leads to higher soil water contents so denitrification rates increase. The silage was irrigated to the same extent as the corn but had lower emissions because it was amended with manure instead of ammonium nitrate fertilizer and total N applied to the silage was less than the corn (Table 4.1). N associated with manure addition is mineralized relatively slowly so less is available for nitrification and denitrification than with fertilizer addition. In all cases except for the irrigated corn grown in the clay loam soil, nitrification was responsible for the majority of total N_2O fluxes. The majority of total fluxes being in the form of NO_x and the small N_2 emissions also resulted from nitrification being a more important agent of N gas loss than denitrification for most of the scenarios considered. The relatively high N_2 loss associated with the irrigated corn grown in clay loam results from denitrification being responsible for the majority of the total N gas flux under this scenario. NO_x, N_2O, and N_2 emissions were not sensitive to no till versus conventional till for winter wheat/fallow cropping simulated with the CPER weather data.

The loam soil driven with weather data from Sterling, Colorado had the highest N gas, NO_x and N_2O emissions for the winter wheat/fallow no till treatment and lowest N gas, NO_x and N_2O emissions for the winter wheat/corn/fallow no till rotations (Figures

4.7a-4.7c). N_2 emissions were highest for the winter wheat/fallow no till rotations and roughly equivalent for the other two options (Figure 4.7d). N_2 emissions contributed less then 3% of the total N gas emissions for each scenario considered with the Sterling weather, indicating that a higher proportion of N gas flux was due to nitrification compared to denitrification. The higher N_2O and N_2 gas emissions for the no till winter wheat/fallow compared to the conventional till winter wheat/fallow is a result of higher denitrification rates in the no till treatment. No till conserves soil moisture which favors the anaerobic conditions that facilitate denitrification. The NO_x/N_2O ratio was lowest for the no till winter wheat/fallow (Figure 4.7e) while the N_2/N_2O ratio was highest for this option (Figure 4.7f). Both of these observations suggest that denitrification, while responsible for a minority of total N gas emissions for these simulations, is relatively more important for the no till winter wheat/fallow system. This is a result of higher water levels associated with no till leading to anaerobic conditions that favor the reduction of NO_x to N_2O and of N_2O to N_2.

More N fertilizer was added with the winter wheat/corn/fallow rotations but total N gas emissions were less (Figure 4.7a). At least two factors besides N additions regulate N gas emissions. First, there is a decrease in the number of fallow months, particularly during the summer, in the 3-year (wwcf-nt) compared to the 2-year rotations (wwf-ct). When the soil is fallow there is no plant uptake of N so more N is available for microbial processes (nitrification and denitrification) that result in N gas emissions. Second, the 3-year rotation leads to an increase in SOM while SOM levels are stable with the conventional winter wheat/fallow system. When SOM is increasing, N availability for processes that result in N gas loss is likely to decrease. The major benefit of the no till system is that it conserves soil water so the fallow period can be reduced without risk of soil water levels dropping too low to support successful cropping. Independent of other factors, no till may induce higher N gas emissions because higher soil water levels in these systems, which tend to be water limited, can facilitate denitrification. The decrease in N gas emissions from reducing the fallow period and from increasing SOM more than compensates for the increase associated with no till, therefore the 3-year no till rotation has lower emissions than the 2-year conventional till rotation.

Comparison of the winter wheat/fallow conventional till and no till options for simulations of the loam soil driven by the CPER weather versus the same options driven by the Sterling weather (Figure 4.8) shows that N_2O and N_2 emissions were higher for the wetter (Sterling) simulations and NO_x emissions were higher for the CPER simulations. Both of these result from higher soil water levels leading to higher denitrification rates and lower nitrification rates in the Sterling soil compared to the drier CPER soil. The winter wheat/fallow rotations were sensitive to tillage type with the Sterling weather but not with the CPER weather. This is a result of interactions with climate. Average annual precipitation is somewhat higher in Sterling (~40 vs. ~35 cm). The higher precipitation coupled with the effects of no till on soil moisture induce denitrification episodes. The effects of a moderate increase in precipitation or of no till cultivation in isolation had little effect on N gas fluxes from the winter wheat/fallow system. But the interaction of these two factors led to increased N_2O emissions because the response of denitrification to soil water content is highly non-linear (Del Grosso et al., 2000a).

Summary and Conclusions

We have described the DAYCENT ecosystem model and shown that annual N_2O emissions can be reliably simulated for some native and managed systems. The model was used to explore how N gas emissions respond to changes in land management, soil texture, and precipitation. Initial values for soil organic C and mineral N levels of the various pools simulated by DAYCENT were obtained by assuming 75 years of winter wheat/fallow cropping. The winter wheat/fallow system has been a common practice in the arid Great Plains but it results in the depletion of SOM. As expected, total N gas and N_2O emissions were higher from fertilized dryland winter wheat/fallow and winter wheat/corn/fallow rotations than native range grass. The highest total N gas and N_2O emissions were from the irrigated perennially cropped corn which had higher levels of N inputs than the dryland cropping. The silage option had N gas emissions similar to the winter wheat/fallow scenarios even though the silage had higher levels of N addition and was irrigated. This can be explained by two factors. First, the silage was amended with manure instead of N fertilizer so a smaller proportion of the applied N was available for nitrification and denitrification. Second, conversion to the silage option resulted in increasing SOM while SOM levels were stable with the winter wheat/fallow systems.

Soil texture had significant effects on total N gas emissions and the relative proportions of the N gas species emitted. NO_x and total N gas emissions tended to decrease as soils became finer textured while N_2O and N_2 emissions tended to increase (Figure 4.6). This is related to the effects of soil texture on gas diffusivity. As soil texture becomes finer water retention tends to increase and gas diffusivity tends to decrease. These conditions contribute to soil anoxia and increase the probability that N oxides produced from nitrification and denitrification will be reduced to N_2O or N_2 before emission from the soil. Simulated denitrification rates are insensitive to soil texture for loam and coarser textured soils but increased substantially in clay loam and finer textured soils. Total N gas losses decreased as soil texture became finer because NO_x emissions decreased and NO_x emissions formed the majority of N gas fluxes. From a greenhouse gas perspective, fine textured soils are expected to emit more N_2O, but from an N balance perspective, fine textured soils are expected to show smaller total N gas losses from the system.

Simulations show that N gas fluxes from soils respond nonlinearly to controls and that interactions among controls are important. Using the CPER weather, tillage type for winter wheat/fallow rotations had little effect on N gas emissions. But with the wetter Sterling data, the no till winter wheat fallow had somewhat higher N_2O and slightly higher NO_x emissions. It is also necessary to consider the interactions between the C and N cycles. Soils that are gaining C will show lower N gas emissions under a given land use than soils that are C saturated. The simulated clay loam soil showed lower total N gas losses because finer textured soils that are C depleted have a higher potential to store C than coarser textured soils. We conclude that mitigation of N gas losses from soils is strongly dependent on land management but that generalizations based solely on soil N and water inputs are likely to be limited because soil texture, SOM levels, and the timing of cropping/fallow seasons are also important.

Acknowledgements

The research for this paper was supported by the National Aeronautics and Space Administration, the National Science Foundation, the Department of Energy and the Environmental Protection Agency through the following grants; NASA-EOS NAGW 2662, NSF-LTER BSR9011659, DOE NIGEC LWT62-123-06516 and EPA Regional Assessment R824939-01-0.

References

Bruce, J.B., M. Frome, E. Haites, H. Janzen,R. Lal and K. Paustian. 1999. Carbon sequestration in soils. J. Soil and Water Conserv. 54:382-389.

Conrad, R. 1996. Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO). Microbiol. Rev. 60:609-640.

Davidson, E.A. 1992. Sources of nitric oxide and nitrous oxide following the wetting of dry soil. Soil Sci. Soc. Am. J. 56:95-102.

Davidson, E.A. 1993. Soil water content and the ratio of nitrous oxide to nitric oxide emitted from soil. p. 369-386. *In* R.S. Oremland (ed.) Biogeochemistry of Global Change: Radiatively Active Trace Gases. Chapman & Hall, New York.

Davidson, E.A., and W. Kingerlee. 1997. A global inventory of nitric oxide emissions from soils. Nut. Cyc. Agroecosys. 48:37-50.

Davidson, E.A., and L. Verchot. Testing the hole in the pipe model of nitric and nitrous oxide emissions from soils using the TRAGNET database. Global Biogeochem. Cycles. 14:1035-1043.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, D.S. Ojima, A.E. Kulmala and S. Phongpan. 2000a. General model for N_2O and N_2 gas emissions from soils due to denitrification. Global Biogeochem. Cycles. 14:1045-1060.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, D.S. Ojima, and M.D. Hartman. 2000b. Interaction of soil carbon sequestration and N_2O flux with different land use practices. p. 303-311. *In* J. van Ham et al. (ed.) Non-CO_2 Greenhouse Gases:

Scientific Understanding, Control and Implementation. Kluwer Academic Publishers, The Netherlands.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. p. 303-332. *In* M. Schaffer et al. (ed.). Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press LLC, Boca Raton, Fl.

Eitzinger, J., W.J. Parton, and M.D. Hartman, improvement and validation of a daily soil temperature submodel for freezing/thawing periods. Soil Sci. (In press.)

Frolking, S.E., A.R. Mosier, D.S. Ojima, C. Li., W.J. Parton, C.S. Potter, E. Priesack, R. Stenger, C. Haberbosch, P. Dörsch, H. Flessa and K.A. Smith. 1998. Comparison of N_2O emissions from soils at three temperate agricultural sites: simulations of year round measurements by four models. Nutr. Cyc. Agroecosys. 52:77-105.

Galloway, J.N., W.H. Schlesinger, H. Levy II, A. Michaels, and J.L. Schnoor. 1995. Nitrogen fixation: Anthropogenic enhancement-environmental response. Global Biogeochem. Cycles. 9:235-252.

Grant, R.F., and E. Pattey. 1999. Mathematical modeling of nitrous oxide emissions from an agricultural field during spring thaw. Global Boigeochem. Cycles. 13:679-694.

Kelly, R.H., W.J. Parton, G.L. Crocker, P.R. Grace, J. Klir, M. Korschens, P.R. Poulton and D.D. Richter. 1997. Simulating trends in soil organic carbon using the century model. Geoderma 81:77-90.

Kelly, R.H., W.J. Parton, M.D. Hartman, L.K. Stretch, D.S. Ojima and D.S. Schimel. 2000. Intra and interannual variability of ecosystem processes in shortgrass steppe. J. Geophys. Res. 105:20,093-20,100.

Kroeze C, A. Mosier, and L. Bouwman. 1999. Closing the global N_2O budget: A retrospective analysis 1500-1994. Global Biogeochem. Cycles. 13:1-8.

Hutchinson, G.L., G.P. Livingston and E.A. Brams. 1993. Nitric and nitrous oxide evolution from managed subtropical grassland. p. 290-316. *In* R.S. Oremland (ed.) Biogeochemistry of Global Change: Radiatively Active Trace Gases. Chapman & Hall, New York.

IPCC (Intergovernmental Panel on Climate Change). 1997. Greenhouse gas emissions from agricultural soils. *In* J.T. Houghton et al. (ed.) Greenhouse Gas Inventory Reference Manual; Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 3, Section 4.5. Agriculture IPCC/OECD/IEA. UK Meteorological Office, Bracknell, UK.

Kelly, R.H., W.J. Parton, G.L. Crocker, P.R. Grace, J. Klir, M. Korschens, P.R. Poulton and D.D. Richter. 1997. Simulating trends in soil organic carbon using the century model. Geoderma 81:77-90.

Kelly, R.H., W.J. Parton, M.D. Hartman, L.K. Stretch, D.S. Ojima and D.S. Schimel. 2000. Intra and interannual variability of ecosystem processes in shortgrass steppe. J. Geophys. Res. 105:20,093-20,100.

Kroeze C, A. Mosier, and L. Bouwman. 1999. Closing the global N_2O budget: A retrospective analysis 1500-1994. Global Biogeochem. Cyc. 13:1-8.

Hutchinson, G.L., G.P. Livingston and E.A. Brams. 1993. Nitric and nitrous oxide evolution from managed subtropical grassland. p. 290-316. *In* R.S. Oremland (ed.) Biogeochemistry of Global Change: Radiatively Active Trace Gases. Chapman & Hall, New York.

Lal, R., J.M. Kimble, R.F. Follett and C.V. Cole. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Ann Arbor Press, Chelsea, MI.

Levin, S.A. 1989. Challenges in the development of a theory of community and ecosystem structure and function. p. 245-255. *In* J. Roughgarden et al. (ed.) Perspectives in Ecological Theory. Princeton University Press, Princeton, New Jersey.

Linn, D.M., and J.W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci. Soc. Am. J. 48:1267-1272.

Martin, R.E., M.C. Scholes, A.R. Mosier, D.S. Ojima, E.A. Holland, and W.J. Parton. 1998. Controls on annual emissions of nitric oxide from soils of the Colorado shortgrass steppe. Global Biogeochem. Cycles. 12:81-91.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton. 1993. CENTURY soil organic matter model environment, Technical documentation, Agroecosystem version 4.0. Great Plains System Research Unit Technical Report No. 4. USDA-ARS, Fort Collins, Colorado.

Mosier, A.R., W.D. Guenzi, and E.E. Schweizer. 1986. Soil losses of dinitrogen and nitrous oxide from irrigated crops in northeastern Colorado. Soil Sci. Soc. Am. J. 50:344-348.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel, and J.A. Delgado. 1996. CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 1. Impact of landscape and nitrogen addition. Global Biogeochem. Cycles. 10:387-399.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel, and O. Hienemeyer. 1997. CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change. Global Biogeochem. Cycles. 11:29-42.

Parton, W. J., and P. E. Rasmussen. 1994. Long-term effects of crop management in wheat/fallow: II. CENTURY model simulations. Soil Sci. Soc. Am. J. 58:530-536.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.J. Scholes, D.S. Schimel, T. Kirchner, J.C. Menaut, T. Seastedt. E. Garcia Moya, Apinan Kamnalrut, and J.L. Kinyamario. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles. 7:785-809.

Parton, W.J., D.S. Ojima, C.V. Cole and D.S. Schimel. 1994. A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. p 147-167. *In* Quantitative Modeling of Soil Forming Processes. SSSA, Spec. Pub. 39. Madison, WI.

Parton, W.J., A.R. Mosier, D.S. Ojima, D.W. Valentine, D.S. Schimel, K. Weier, and K.E. Kulmala. 1996. Generalized model for N_2 and N_2O production from nitrification and denitrification. Global Biogeochem. Cycles. 10:401-412.

Parton, W.J., M. Hartman, D.S. Ojima and D.S. Schimel. 1998. DAYCENT: Its land surface submodel: description and testing. Global Planetary Change. 19:35-48.

Parton, W.J., E.A. Holland, S.J. Del Grosso, M.D. Hartman, R.E. Martin, A. R. Mosier, D.S. Ojima and D.S. Schimel. Generalized Model for NO_x and N_2O Emissions from Soils. J. Geophys. Res. (In press.)

Paustian, K., W.J. Parton and J. Persson. 1992. Modeling soil organic matter in organic amended and nitrogen-fertilized long term plots. Soil Sci. Soc. Am. J. 56:476-488.

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Till. Res. 47:207-218.

Potter, C.S., E.A. Davidson, and L.V. Verchot. 1996. Estimation of global biogeochemical controls and seasonality in soil methane consumption. Chemosphere. 32:2219-2245.

Prather, M.J., R.Derwent, D. Ehhalt, P. Fraser, E. Sanhueza, and X. Zhou. 1995. Other trace gases and atmospheric chemistry. p. 73-126. *In* J.T. Houghton et al. (ed.) Climate Change 1994. Cambridge University Press, Cambridge, UK.

Robertson, G.P., E.A. Paul, and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science. 289:1922-1925.

Smart, D.R., J.M. Stark, and V. Diego. 1999. Resource limitation to nitric oxide emissions from a sagebrush-steppe ecosystem. Biogeochem. 47:63-86.

Smil, V., 1999. Nitrogen in crop production: An account of global flows. Global Biogeochem. Cycles. 13:647-662.

Vitousek, P.M. and R.W. Howarth. 1991. Nitrogen limitation on land and in the sea: How can it occur? Biogeochem. 13:87-115.

Vitousek, P.M., J. Aber, E.H. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, D.G. Tilman. 1997. Human alteration of the global nitrogen cycle: causes and consequences. Issues in Ecology. 1:1-15.

Williams, E.J., G.L. Hutchinson, and F. Fesenfeld. 1992. NO_x and N_2O emissions from soil. Global Biogeochem. Cycles. 6:351-388.

Yienger, J.J. and H. Levy. 1995. Empirical model of global soil biogenic NO_X emissions. J. Geophys. Res. 100:11447-11464.

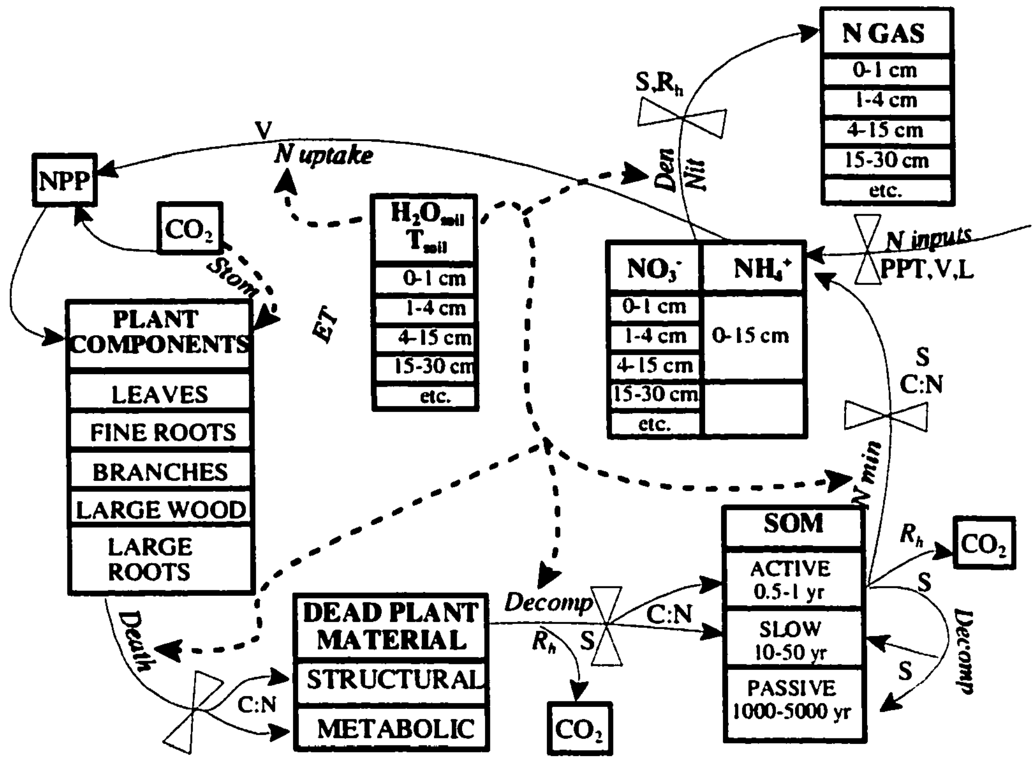
Tables

Table 4.1. Land management practices simulated by DAYCENT

crop/vegetation	N addition ($gN\ m^{-2}\ yr^{-1}$)	CPER weather month(s) of N addition	irrigation	tillage
wwf-ct	2.5	9,4	no	conventional
wwf-nt	2.5	9,4	no	no till
corn	10	5,7	yes	conventional
sil	6.25^{m}	12	yes	conventional
rg	0		no	none
		Sterling weather		
wwf-ct	2.5	9,4	no	conventional
wwf-nt	2.5	9,4	no	no till
wwcf-nt	3.3	$9^{w},4^{w},5^{c}$	no	no till

wwf-ct = winter wheat/fallow rotations, conventional till
wwf-nt = winter wheat/fallow rotations, no till
corn = perennial corn cropping, conventional till
sil = perennial silage cropping, conventional till
rg = native range grass, grazed from April-November
wwcf-nt = winter wheat/corn/fallow rotations, no till
^{m} = N from manure, all others from ammonium nitrate fertilizer
^{w} = fertilizer application for winter wheat years
^{c} = fertilizer application for corn year

List of Figures



→ = C, N flows

- - → = Feedbacks, information flows

= Control on process

H_2O_{soil} = Soil water content

T_{soil} = Soil temperature

S = Soil texture

C:N = Carbon:Nitrogen ratio of material

V = Vegetation type

SOM = Soil Organic Matter

L = Land use

R_h = Heterotrophic respiration

N GAS = N_2O, NO_X, N_2

Processes designated by *italics*

Stom = Stomatal conductance

Death = Plant component death

Decomp = Decomposition

N inputs = N Fixation, N deposition, N fertilization

Nit = Nitrification

Den = Denitrification

N min = N mineralization

ET = Evapotranspiration

Figure 4.1

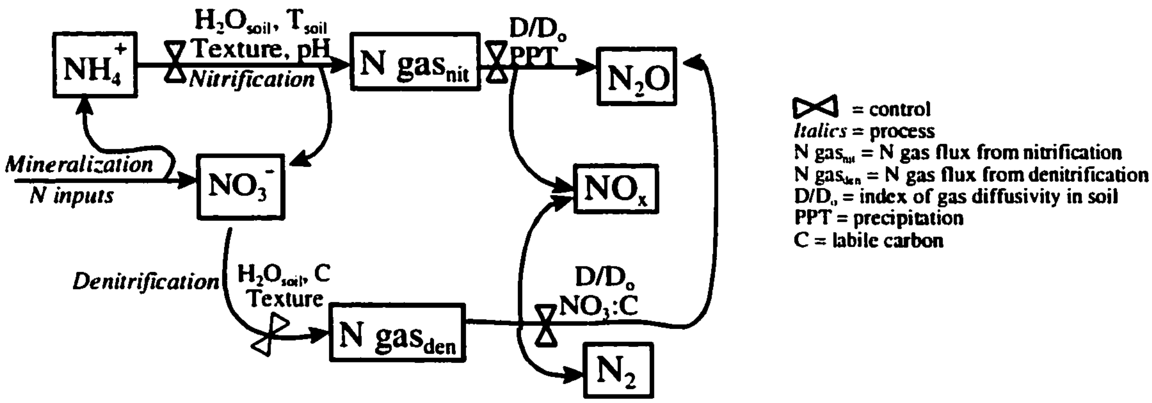


Figure 4.2

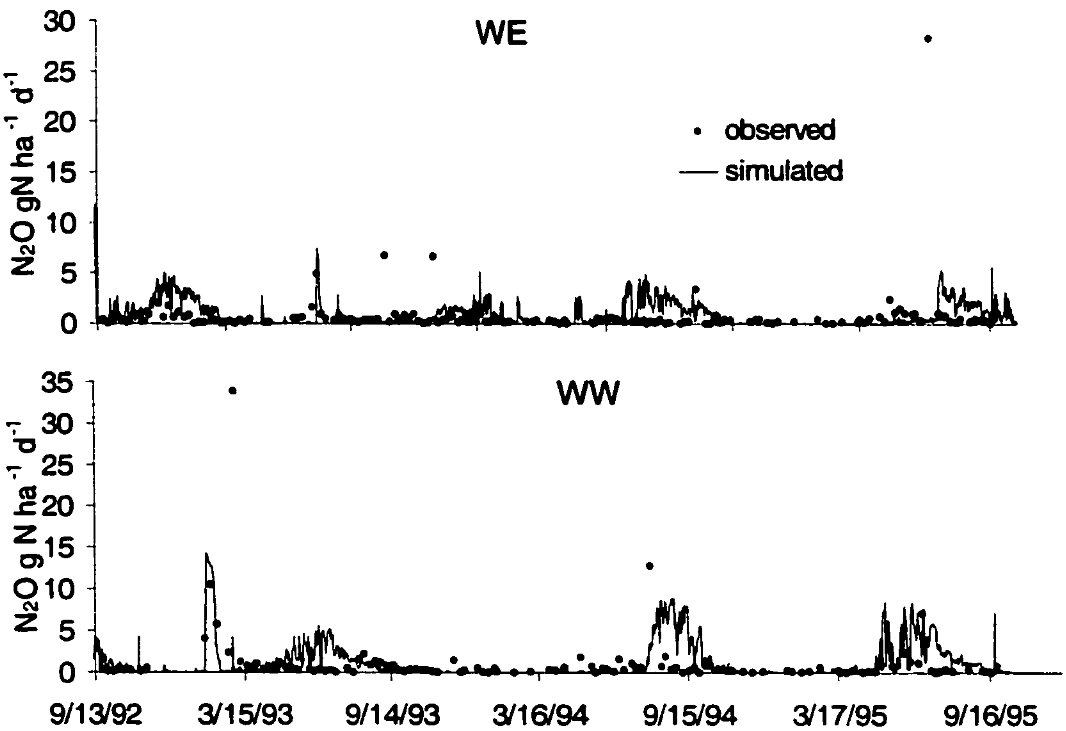


Figure 4.3

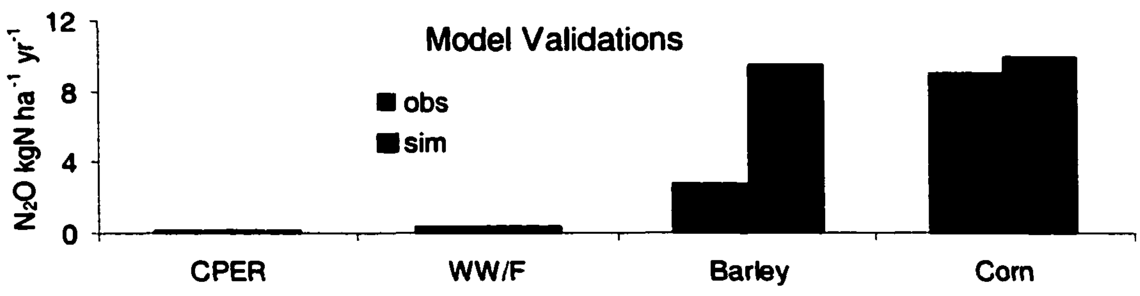


Figure 4.4

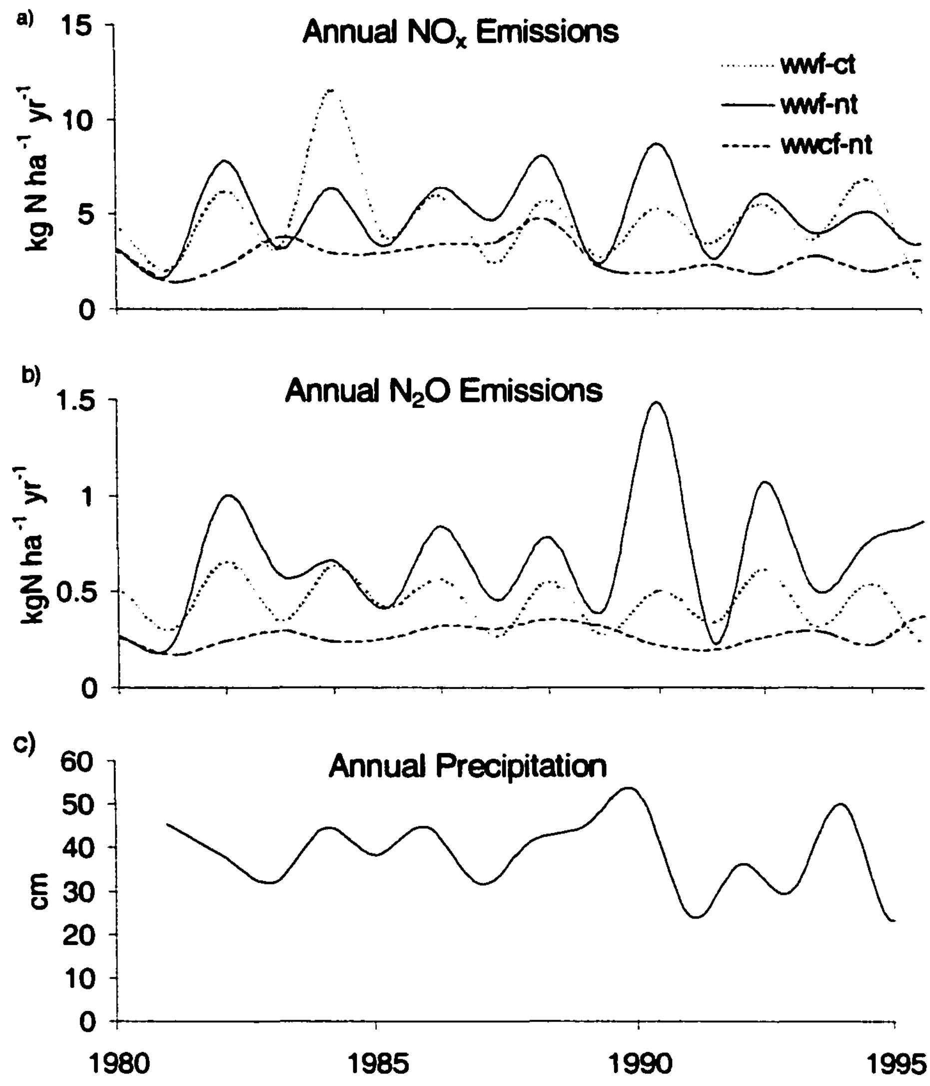


Figure 4.5

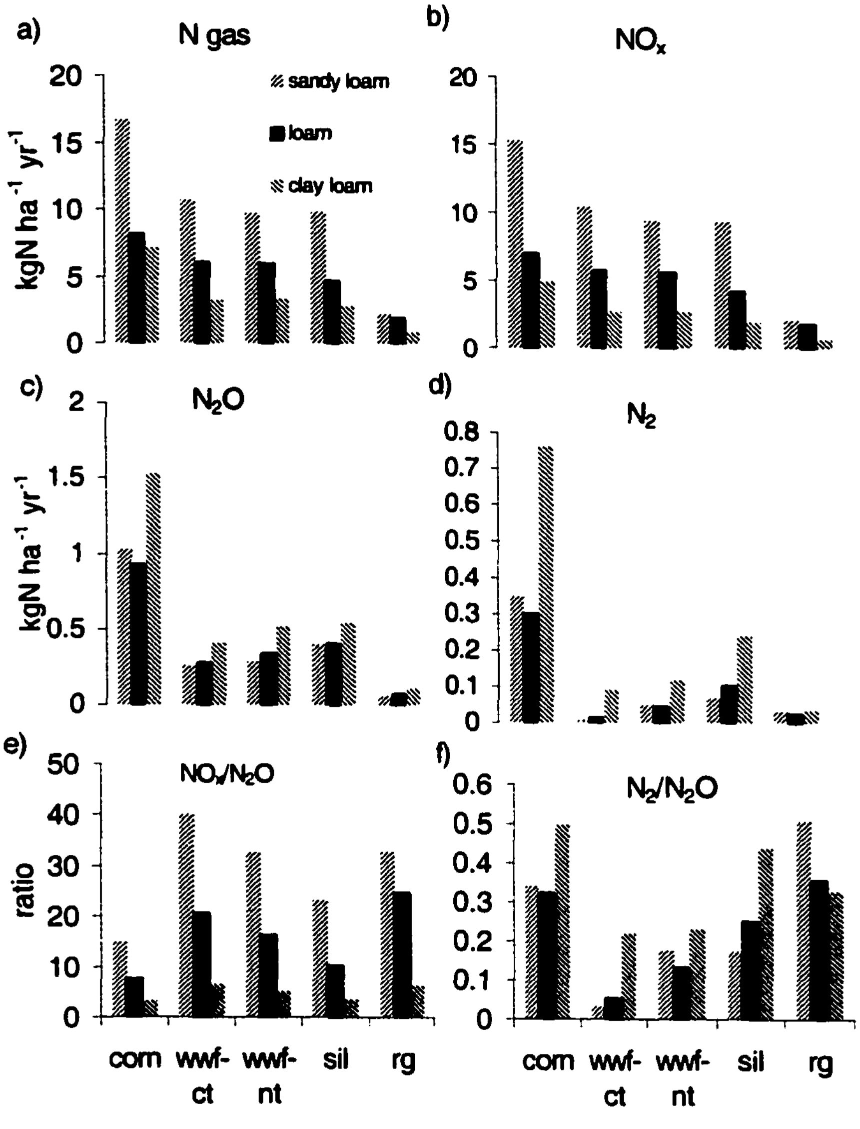
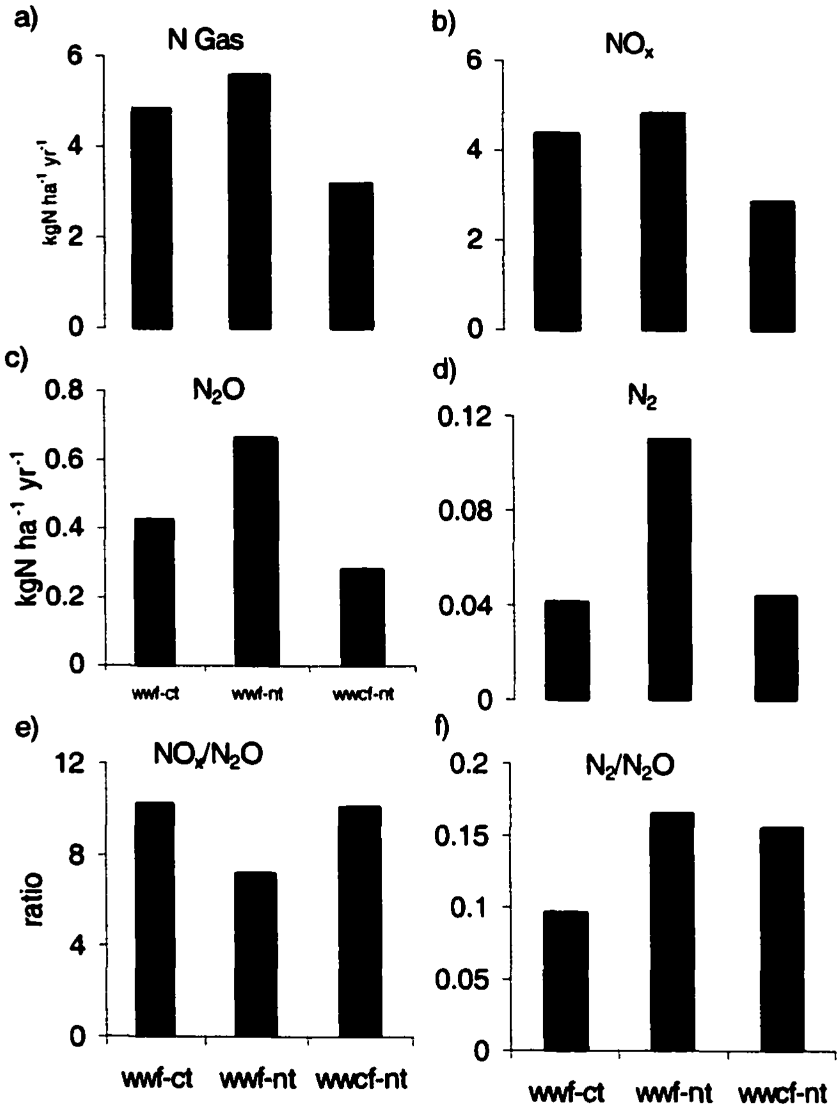
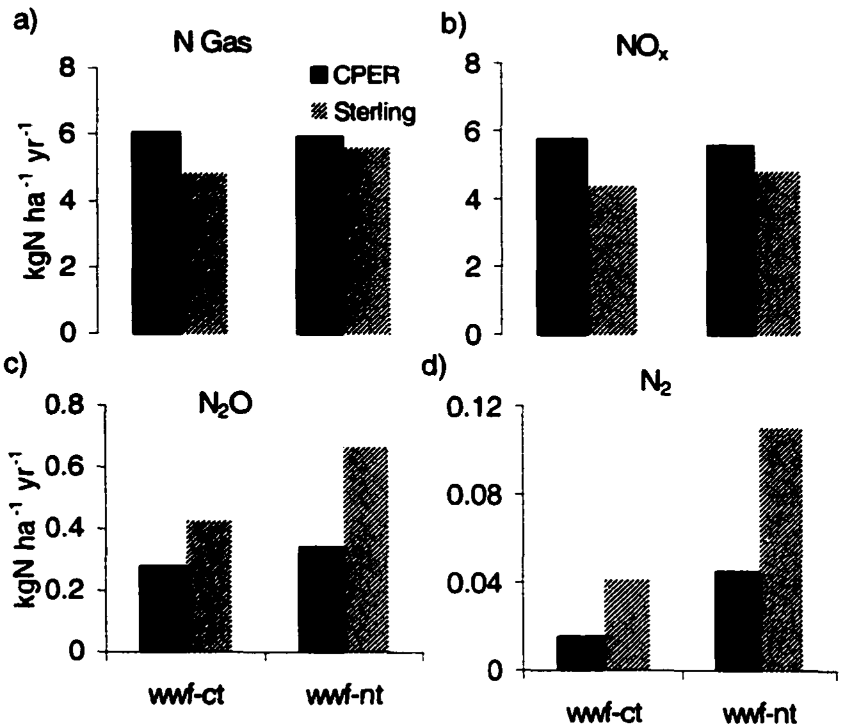

a)
N gas
sandy loam
loam
clay loam
kgN ha-1 yr-1
20
15
10
5
0
b)
NOx
20
15
10
5
0
c)
N2O
2
1.5
1
0.5
0
d)
N2
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
e)
NOx/N2O
ratio
50
40
30
20
10
0
f)
N2/N2O
0.6
0.5
0.4
0.3
0.2
0.1
0
corn
wwf-ct
wwf-nt
sil
rg

Figure 4.6



a)
N Gas
kgN ha-1 yr-1
6
4
2
0
b)
NOx
6
4
2
0
c)
N2O
kgN ha-1 yr-1
0.8
0.6
0.4
0.2
0
wwf-ct
wwf-nt
wwcf-nt
d)
N2
0.12
0.08
0.04
0
e)
NOx/N2O
ratio
12
8
4
0
wwf-ct
wwf-nt
wwcf-nt
f)
N2/N2O
0.2
0.15
0.1
0.05
0
wwf-ct
wwf-nt
wwcf-nt

Figure 4.7



a)
N Gas
CPER
Sterling
kgN ha-1 yr-1
8
6
4
2
0
b)
NOx
8
6
4
2
0
c)
N2O
kgN ha-1 yr-1
0.8
0.6
0.4
0.2
0
wwf-ct
wwf-nt
d)
N2
0.12
0.08
0.04
0
wwf-ct
wwf-nt

Figure 4.8

Chapter 5

Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes using the DAYCENT Model

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S., Schimel, D.S., 2001. In: Schaffer, M., et al. (Eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*, p. 303-332, CRC Press.

Introduction

Cycling of carbon (C) and nitrogen (N) among living and non-living systems interacts with climate to maintain the environmental conditions that support life on Earth. Industrialization and human population growth have profoundly altered C and N flows. The human induced input of reactive N into the global biosphere increased to approximately 150 Tg N (1 Tg = 10^{12} g) in 1996 and is expected to continue to increase for the foreseeable future (Bumb and Baanante, 1996; Smil, 1999). Of this 150 Tg N about 85 Tg is from synthetic fertilizer, ~35 Tg is from biological N-fixation in crops and ~ 25 Tg is generated from fossil fuel combustion. This input of newly fixed N into the biosphere exceeds the N fixed annually in natural ecosystems (Smil, 1999; Vitousek et al. 1997; Galloway et al. 1995). Atmospheric CO_2 concentration has been increasing since the industrial revolution because the sum of CO_2 emissions from fossil fuel combustion and respiration in natural and agricultural systems exceeds the uptake of CO_2 by photosynthesis and by transport to deep ocean water. Changes in the pool sizes of some important compounds of C and N have been reliably measured, e.g. the current and historical atmospheric concentrations of the long lived trace gases CO_2, CH_4, and N_2O have been well documented (Prather et al., 1995). However, the absolute and relative contributions of the terrestrial and aquatic systems that act as sources and sinks of C and N are somewhat uncertain (Matson and Harris, 1995). Complete accounting of C and N flows through ecosystems by direct measurement would require continuous, spatially intensive monitoring at various scales and thus, is not practically feasible. Models test our understanding of the controls on biogeochemical processes and are necessary to scale up results of plot size measurements and calculate the contributions of various natural and managed ecosystems to global C and N budgets.

Ecosystem models can be classified along a spectrum that includes at one extreme complex models that explicitly simulate the biological, chemical, and physical processes that control C and N flows. For example, the model *ecosys* (Grant et al., 1993) simulates microbial growth, aqueous and gaseous transport of metabolic reactants and products, as well as other small scale processes to model large scale ecosystem characteristics such as N_2O emissions (Grant and Pattey, 1999) from soils. At the other extreme, simple, empirical models correlate ecosystem scale processes with parameters that are frequently measured in the field. For example, the Miami model (Lieth, 1975) has been used to calculate global net primary productivity (NPP) from average annual precipitation and temperature values (Alexandrov et al., 1999). Complex models require detailed parameterization and intensive computation and the usefulness of highly mechanistic models for ecosystem managers has been questioned (Nuttle, 2000). Simpler models are also of limited use to managers because they are likely to be overly generalized and cannot represent the heterogeneity characteristic of most real world systems. DAYCENT (Kelly et al., in press; Parton et al., 1998) is a terrestrial ecosystem model used to simulate exchanges of C, N, and trace gases among the atmosphere, soils, and vegetation. DAYCENT is of intermediate complexity, important processes are represented mechanistically but the model makes use of empirically derived equations and the required input parameters are often available for many regions.

First, we describe the DAYCENT model in detail. Then, observed and simulated values of soil water content, temperature, mineral N, and N gas emissions from native and agricultural soils in Colorado will be compared to demonstrate the validity of DAYCENT. Lastly, we present an application of the model to calculate net greenhouse gas emissions associated with alternative crop management practices for a typical Midwestern U.S. soil and a typical U.S. Great Plains soil. Sequestration of C in soil organic matter has been suggested as a means to compensate for emissions of greenhouse gases associated with human activities (Bruce et al., 1999, Lal et al., 1998). Although addition of fertilizer to soils often results in an increase in soil C, objectivity requires that the greenhouse gas emissions associated with N fertilizer production and application be included in a total greenhouse gas accounting. N fertilizer manufacture requires energy consumption resulting in CO_2 emissions and application of N fertilizer typically results in elevated emissions of nitrous oxide (N_2O), an important greenhouse gas (Granli and Bockman, 1994). Agricultural soils amended with N fertilizer also can contribute to nitrate

(NO_3^-) leaching and reduce the quality of water that supplies underground aquifers, waterways and estuaries. DAYCENT simulations were used to explore how different land management strategies effect soil C and N levels, N_2O emissions, net C storage, NO_3^- leeching, and crop yields associated with a Great Plains soil that has been used for winter wheat/fallow rotations for at least 60 years and a Midwestern soil that has been used for corn/winter wheat/pasture rotations for over 100 years.

DAYCENT Model Description

DAYCENT (Parton et al., 1998, Kelly et al., in press) is the daily time step version of the CENTURY ecosystem model. CENTURY (Parton et al., 1994) operates at a monthly time step because this degree of resolution is adequate for simulation of medium to long term (10 - >100 years) changes in soil organic matter (SOM), plant productivity, and other ecosystem parameters in response to changes in climate, land use, and atmospheric CO_2 concentration. However, simulation of trace gas fluxes through soils requires finer time scale resolution because a large proportion of total gas fluxes are often the result of short term rainfall, snow melt or irrigation events (Frolking et al., 1998; Martin et al., 1998) and the processes that result in trace gas emissions often respond non-linearly to changes in soil water levels. DAYCENT and CENTURY both simulate exchanges of carbon and the nutrients nitrogen (N), potassium (P), and sulfur (S) among the atmosphere, soil, and plants and use identical files to simulate plant growth and events such as fire, grazing, cultivation, harvest, and organic matter or fertilizer additions. In addition to modeling decomposition, nutrient flows, soil water and soil temperature on a finer time scale than CENTURY, DAYCENT also has increased spatial resolution for soil layers.

layers by assuming that the concentrations of mineral N and SOM are highest near the soil surface and drop exponentially with depth. NO_3^- and NH_4^+ are available for both plant growth and for biochemical processes that result in N transformations (nitrification and denitrification) and N gas emissions. Significant amounts of NO_3^- can be lost from soils via leaching when water flow through the soil profile is sufficiently high. A detailed description of the SOM model used in DAYCENT can be found in Parton et al. (1993) and Parton et al. (1994).

Plant Growth Submodel

The DAYCENT plant production submodel (Metherell et al., 1993) can simulate the growth of various crops, grasses and trees. However, only one type of grass (or crop) and one type of tree can be simulated at a time along with competition between the grass/crop and trees. Different crop, grass and forest systems are distinguished by varying the parameters that control maximum growth rate, C allocation among plant parts and the C:N ratios of plant parts. The model also simulates disturbance events such as burning, grazing and plowing, as well as addition of water and nutrients via irrigation, fertilization, organic matter application, N deposition and N fixation. For a given grass/crop, forest, or savanna (tree and grass) system, plant production is controlled by a maximum plant growth parameter, nutrient availability, and 0-1 multipliers that reflect shading, water, and temperature stress. Parameters in the equations that account for shading, water and temperature limitation, maximum plant growth rate, ranges of C:N ratios for plant compartments, etc. can be adjusted to reflect the physiological properties of various vegetation types and particular species of grasses, crops, or trees.

The grass/crop submodel (Figure 5.2) divides plant biomass among grain, shoot, and root compartments, while the forest submodel divides biomass among leaves, fine branches, large wood, fine roots, and coarse roots. The allocation of Net Primary Productivity (NPP) among plant compartments is a function of season, the relative sizes of the compartments, tree age, precipitation, and nutrient availability. The proportion of NPP allocated to roots increases as precipitation decreases and can be made a function of time since planting for crops. The N, P and S concentrations of biomass in the plant compartments are functions of nutrient availability and the component specific C to element ratio ranges for these nutrients. Plant material death rate is a function of soil water content and a plant component specific death rate. Coniferous and deciduous tree leaves have a death rate that changes monthly while deciduous tree leaves also have a much higher death rate during the senescence month. Biomass can be removed or transferred to the litter pool by disturbance events such as harvesting, grazing, plowing, burning, clear cutting, etc.. Disturbance events affect both the quantity and nutrient concentration of litter that supplies the SOM pool. For example, fire volatilizes some C and nutrients from the live biomass and litter pools but the ash provides a nutrient rich soil input.

Land Surface Submodel

The land surface submodel of DAYCENT (Parton et al. 1998) simulates water flow through the plant canopy, litter and soil (Figure 5.3), as well as soil temperature. Water content and temperature are simulated for each soil layer. Different types of soils can be represented by varying the number of soil layers simulated, the thickness of each layer, and the depth of the soil profile. An example of a 12 layer structure that we have used is: 0-1cm, 1-4cm, 4-15cm, 15-30cm 30-45 cm, ...135-150cm. Model inputs include daily precipitation, maximum and minimum air temperature values, soil bulk density (BD), field capacity (FC), saturated hydraulic conductivity (K_{sat}), and the proportion of plant roots for each layer. Precipitation that is intercepted by vegetation and litter is evaporated at the potential evapotranspiration rate (PET). The amount of precipitation intercepted is a function of the total amount of precipitation, the above ground biomass, and litter mass. When the average daily air temperature is below freezing precipitation is assumed to fall as snow and is accumulated in the snowpack. Precipitation that is not intercepted and water inputs from snow melting or irrigation infiltrate the soil or run off of the soil surface. Soil saturated flow and surface runoff are simulated first, then water is evaporated and distributed throughout the soil profile using an unsaturated flow algorithm. PET is calculated using the equation of Penman (1948) and the actual evapotranspiration rate (AET) is limited by soil water potential in the root zone. As biomass decreases transpiration is assumed to decrease and evaporation increases (Parton, 1978).

Soil water input events initiate a 4 hour infiltration/saturated flow period that is unidirectional downward and each layer is filled before water flows to the next layer. If water input rate is greater than K_{sat} (cm s^{-1}) the difference goes to surface runoff. The K_{sat} of frozen soil is greatly reduced. After the 4 hour input event ends, water in excess of field capacity is drained into the layer below it. Water that exits the bottom layer of the soil profile goes to outflow and can include leached NO_3^-.

Unsaturated, bidirectional flow is calculated using Darcy's law as a function of the hydraulic conductivity of the soil layers and the difference in hydraulic potential calculated at the centers of adjacent soil layers. The gravitational head and matric potential are summed to obtain the hydraulic potential for each layer. Flux out of the top layer depends on PET, the water content of the top layer, and the minimum water content designated for the top layer. The calculated water fluxes are adjusted if the flow would dry a layer below its minimum allowable water content.

The temperature submodel (Eitzinger, et al., in press; Parton, 1984) calculates thermal diffusivity and daily maximum/minimum temperature for each soil layer. Inputs include daily maximum/minimum air temperatures at 2 meters, plant biomass, snow cover, soil moisture, soil texture, and day length. The upper boundary for the one-dimensional heat flow equation is the soil surface temperature and the lower boundary is a sine function of the Julian date and the average annual temperature at the bottom of the soil profile. Soil surface temperature is a function of the maximum/minimum air temperature, snow cover, plant biomass and litter. As snow cover, plant biomass, or litter increases, maximum and minimum soil temperature values are less responsive to changes in air temperature.

N Gas Submodel

The N gas submodel (Parton et al., submitted, Del Grosso et al., in press) of DAYCENT simulates N_2O, NO_x, and N_2 gas emissions from soils resulting from nitrification and denitrification. Nitrification is an aerobic process in which NH_4^+ is oxidized to NO_3^-, with N_2O and NO_x being released as by-products during the intermediate steps (Figure 4). DAYCENT assumes that releases of N gases from soils due to nitrification are proportional to nitrification rates and that nitrification rates are controlled by soil NH_4^+ concentration, water content, temperature, pH, and texture (Parton et al., 1996; Parton et al., submitted). For a given soil NH_4^+ concentration, nitrification increases with soil temperature (T_{soil}) until T_{soil} reaches the average high temperature for the warmest month of the year. Nitrification is assumed to be not limited by temperature when T_{soil} exceeds the site specific average high temperature for the warmest month of the year. Nitrification is limited by moisture stress on microbial activity when WFPS (water-filled pore space) is low and by O_2 availability when WFPS is high. Peak nitrification rates are assumed to occur when soil water content is ~50% WFPS, with finer textured soils having a slightly higher optimum WFPS. Nitrification is not limited when pH is greater than 7 but decreases exponentially as pH falls below 7 due to acidity.

Denitrification is biochemical process in which heterotrophic microbes reduce NO_3^- to NO_x, N_2O, and N_2 under anaerobic conditions. The denitrification submodel (Del Grosso et al., in press; Parton et al. 1996) first calculates total N gas flux from denitrification (N_2+N_2O) then uses a N_2/N_2O ratio function to infer N_2O and N_2 emissions (Figure 5.4). Denitrification is controlled by labile C availability (e^- donor), soil NO_3^- concentration (e^- acceptor), and O_2 availability (competing e^- acceptor). Modeled soil heterotrophic respiration is used as a proxy for labile C availability. O_2 availability is a function of soil WFPS and O_2 demand. O_2 demand is a function of simulated heterotrophic CO_2 respiration and soil gas diffusivity. Gas diffusivity is calculated as a function of soil WFPS, bulk density, and field capacity according to equations presented by Potter et al. (1996). The model predicts that O_2 is readily available, and little denitrification can occur, in coarse textured soils with high gas diffusivity unless WFPS exceeds ~80% WFPS. However, fine textured soils with low gas diffusivity are predicted to contain a substantial proportion of aggregates which can become anaerobic when O_2 demand is high and facilitate denitrification at WFPS values as low as 60%. The ratio of N_2/N_2O gases emitted from soil due to denitrification is a function of soil gas diffusivity and the ratio of e^- acceptor (NO_3^-) to e^- donor (labile C). The probability that N_2O produced from denitrification is further reduced to N_2 before diffusing from the soil surface increases as gas diffusivity decreases because residence time in the soil increases. The ratio of N_2/N_2O is high when labile C is in excess compared to NO_3^- because N_2O can act as an alternative e^- acceptor when NO_3^- is in short supply.

On a daily time step, simulated values of soil NH_4^+, NO_3^-, CO_2, water content, and temperature are used to calculate N_2O and N_2 emissions from nitrification and denitrification for each soil layer, then the N gas values are summed to yield simulated N_2O and N_2 gas emissions for the soil profile. NO_x emissions are a function of total N_2O emissions from nitrification and denitrification, a NO_x/N_2O ratio function, and a pulse multiplier (Parton et al., submitted). The majority of NO_x emissions from soil are assumed to be from nitrification because NO_x is highly reactive under the reducing conditions that facilitate denitrification (Conrad, 1996). The NO_x/N_2O ratio is low (~1) when gas diffusivity, and hence O_2 availability, is low because denitrification is the dominant process under such conditions. The ratio increases to a maximum of ~20 as gas diffusivity increases because nitrification dominates when soils are well aerated. The modeled total N_2O emission rate is multiplied by the ratio function to obtain a base NO_x emission rate. The base NO_x emission rate may be modified by a pulse multiplier. Large pulses of NO_x are often initiated when precipitation falls on soils that were previously dry independent of other controlling factors (Smart et al., 1999; Martin et al., 1998; Hutchinson et al., 1993). The pulses are thought to be related to substrate accumulation and activation of water stressed bacteria upon wetting (Davidson, 1992). To account for these pulses the model incorporates the pulse multiplier submodel described by Yienger and Levy (1995). The magnitude of the multiplier is proportional to the amount of precipitation and the number of days since the precipitation event, with a maximum multiplier of 15. N balance is verified on a daily basis and calculated N gas emission rates are revised downwards if there is not enough NO_3^- and NH_4^+ available to supply the calculated N gas emission for that day.

Model Validation

The CENTURY model has been used to successfully simulate SOM and N cycling in various natural and managed systems (Kelly et al., 1997; Parton and Rasmussen, 1994; Paustian et al., 1992). The ability of DAYCENT to simulate soil water content, mineral N, and N_2O and CO_2 emissions from field sites in Scotland, Germany, and Colorado was demonstrated and compared to alternative models by Frolking et al. (1998). Simulated values of soil water content, temperature, and N_2O and NO_x emissions were shown to agree favorably with observed data from rangeland soils of varying texture and fertility levels (Parton et al., submitted). Here we present results of model simulations of soil water content, temperature, mineral N concentration, and N_2O

emissions from rangeland (Mosier et al., 1996) and from fertilized, irrigated corn and barley crops in northeastern Colorado (Mosier et al., 1986). Mosier et al. (1996) collected weekly soil water, temperature and N gas flux data from soils of different textures and fertility levels at the Central Plains Experimental Range (CPER). The CPER has an average annual precipitation of 35 cm and texture ranges from sandy loam to clay loam. Mosier et al. (1986) collected soil water, temperature, mineral N, and N_2O gas flux data from a field used for corn cropping in 1982 and barley cropping in 1983. The soil used for the corn and barley cropping is a moderately well drained Nunn clay. It was amended with 20 gN m^{-2} yr^{-1} of ammonium sulfate, $(NH_4)_2SO_4$, and irrigated during the growing season (Mosier et al., 1986). Measured values of soil C, mineral N, texture and bulk density (Mosier et al., 1996) were used to initialize the SOM and nutrient pools and to parameterize soil physical properties (field capacity, wilting point, K_{sat}). No model coefficients or equations were adjusted for the validation simulations. We first consider how well DAYCENT simulated the drivers of the N gas submodel then compare observed and simulated N_2O emissions.

Figures 5.5a and 5.5b show the observed and simulated time series for soil water content and temperature for a representative year of measurements for a native sandy loam soil at the CPER. Temperature was simulated well during all seasons but the model failed to simulate the variability in soil water observed during the spring and winter months. The poor model performance during the non-growing season is related to high spatial heterogeneity of measured soil water content from snow drifting and melting. The model simulated the trends in soil water content correctly for the cropped soil (Figure 5.5c) but did not dry to the extent indicated by the data. Similarly, the model simulated the general trends in soil temperature (Figure 5.5d) but some data points were greatly over or under estimated. Figure 5.6a shows that the model correctly simulated high NH_4^+ levels after fertilization events for the cropped soil and the observed depletion of NH_4^+ from plant uptake and nitrification. The measured soil NO_3^- concentrations were quite variable but the model exhibited the general pattern of the data, high levels in the spring and decreasing NO_3^- during the growing season (Figure 5.6b). Figures 5.6c and 5.6d show the observed and simulated N_2O gas emissions from the native sandy loam pasture at the CPER for a representative year and from the corn and barley crops. Although the day to day variability is high, DAYCENT captured the monthly and seasonal trends in N_2O emissions from the native soil well, although winter season fluxes tended to be under-estimated. The model represented the daily variability and seasonal patterns of N_2O emissions from the corn crop (1982) reasonably well. However, N_2O emissions were greatly overestimated for the barley (1983). The overestimation of N_2O emissions in May and June is due to denitrification events simulated by DAYCENT. Mosier et al. (1986) pointed out that that the spring of 1983 was unusually wet and soil water content was at or near field capacity most of the time but the expected N_2O emissions from denitrification (an anaerobic process) were not observed. We speculate that C availability may have been limiting denitrification in the spring and that the model overestimated C availability.

These results show that DAYCENT generally simulates the inputs used to calculate N gas emissions reasonably well but that high spatial or temporal variation in the data can contribute to a poor comparison between observed and simulated values. Comparisons with observed data from the CPER showed that soil WFPS was modeled significantly better in the growing season compared to the winter with r^2 values of 0.66 and 0.28, respectively, for aggregated multiyear data from rangeland soils of varying texture and fertility levels. Variability in N gas submodel inputs and high coefficients of variation for measured N_2O flux rates contribute to the lack of fit on a daily scale between observed and simulated N_2O emission rates (Figures 5.6c, 5.6d). Although the model often miss-times large N_2O flux events, on average, the model mimicked the seasonal trends in N_2O flux well, except for the barley crop.

A more extensive validation of DAYCENT (Parton et al., submitted) showed that seasonal N gas fluxes were fairly well represented by the model with observed versus simulated r^2 values of 0.29 and 0.43 for monthly N_2O and NO_x emissions, respectively, for the combined data from 5 soils of different texture and fertility levels. Frolking et al. (1998) compared the ability of DAYCENT and three other models to simulate the observed soil water content and N_2O emissions from soils in Colorado, Scotland and Germany. The Colorado site is a dry shortgrass steppe, the Scotland site is a fairly wet ryegrass pasture, and the German sites are perennially cropped. Average yearly N_2O emissions varied by a factor of ~100 among these sites. DAYCENT correctly simulated the high N_2O emission rates from the agricultural soils, the intermediate N_2O emission rates from the pasture, and the very low N_2O emission rates from the shortgrass steppe. DAYCENT also simulated reasonably well the daily variations in N_2O emission rates and soil water content observed at the respective sites (Frolking et al., 1998).

Model Application

We used DAYCENT to compare the tradeoffs involving net greenhouse gas emissions, NO_3^- leaching, and crop yields associated with different land use scenarios in a Great Plains soil used for winter wheat/fallow rotations and Midwestern soil used for corn/winter wheat/pasture rotations. For the Great Plains soil, alternatives to conventional winter wheat/fallow cropping that have been suggested to increase SOM include no till winter wheat cropping, perennial cropping of corn, corn/soybeans and silage, and reversion to rangeland. The management alternatives considered for the Midwestern soil included continuous corn and corn/soy bean rotations, each under conventional or no till cultivation.

To compare the net greenhouse gas effect of the management options we simulated SOM levels and inferred the flux of CO_2 between the atmosphere and the soil from changes in system C values. System C, the sum of C in soil organic matter, surface organic matter, and surface litter, is used because the effects of management options should consider residue C on the soil surface, as well as soil C (Peterson et al., 1998). We also simulated the N_2O emissions for each option and calculated a yearly CO_2 equivalent for N_2O gas emissions by assuming that each N_2O molecule has 310 times the global warming potential of a CO_2 molecule (Prather et al., 1995). The greenhouse gas emissions of N fertilizer production were calculated by assuming that each gram of N fertilizer results in the release of 0.8 g CO_2-C due to fossil fuel combustion (Schlesinger, 1999). The preceding three quantities were summed to obtain a measure of the net greenhouse contribution associated with each land use practice. Crop yields and NO_3^- leaching associated with the management alternatives were also compared. We first present an analysis for the relatively dry Great Plains soil similar to that performed by Del Grosso et al. (2000) using an earlier version of DAYCENT and then present the results of the simulations for the wetter Midwestern soil.

Simulation of conventional winter wheat/fallow rotations and 6 alternatives

The crop/fallow system is used to grow winter wheat in the Great Plains because precipitation ranges from 30 to 60 cm per year and this region often experiences drought conditions. In order to conserve soil water, the land is left to lie fallow for a season after each cropping period. This practice results in a significant decrease (~50%) in SOM after 30-50 years (Peterson et al., 1998). Measured texture and bulk density values for a sandy loam soil from the Central Plains Experimental Range (CPER) in northeastern Colorado (Mosier et al. 1996) were used to parameterize soil physical properties for the simulations. DAYCENT was run for 100 years of winter wheat/fallow rotations (1880-1980) using a weather file from the CPER to initialize the SOM and nutrient pools. The average annual precipitation for this weather file is 35 cm and the average annual temperature is 9.5 °C. The model was then run for another 100 years (1981-2080) of conventional till winter wheat/fallow rotations (wwct) and 6 alternative management scenarios (Table1); no till winter wheat/fallow rotations (wwnt), perennial corn cropping (corn), corn/alfalfa rotations (corn/alf), range grass (rg), fertilized range grass (rg + N), and continuous silage cropping (silage). Fertilizer was added in the form of ammonium nitrate. The corn, corn/alf and silage alternatives included irrigation during the growing season (May-October). The winter wheat was fertilized during the planting month (September), and in April of the following year before harvest in July. The simulated fallow period was from August of the harvest year through August of the following year. The simulated conventional tillage winter wheat/fallow soil had a 1995 SOM value of ~ 1.3 kgC m^{-2} soil which agrees closely with measured values (1.4-1.5 kgC m^{-2} soil) for a similar soil used for winter wheat/fallow rotations for many years (Mosier et al., 1997). Yearly values of soil C, NO_3^- leached, N_2O gas emitted, and above ground NPP were compiled for winter wheat/fallow cropping and each alternative scenario.

Figure 5.7a shows that winter wheat/fallow rotations maintain soil C at fairly low levels. Alternative scenarios that included perennial cropping, N addition and irrigation (corn, corn/alfalfa, and silage) showed significant increases in SOM. Reversion to native rangeland or conversion to no till wheat/fallow rotations resulted in a small increase of SOM compared to the standard winter wheat/fallow conventional till practice. However, conversion to rangeland augmented with a small amount of N fertilization resulted in sustained increases of SOM. The scenarios that included irrigation and N fertilization (corn and corn/alfalfa) emitted much more N_2O than the other alternatives (Figure 5.7b). Corn/alfalfa rotations had the highest N_2O emissions with the corn years showing higher emissions than the alfalfa years. Perennial silage cropping augmented with manure resulted in only slightly higher N_2O emissions than the conventional winter wheat/fallow system. No till winter/wheat fallow rotations showed similar N_2O emissions as the conventional till winter wheat/fallow cropping, with the vast majority of the N_2O emitted during the fallow season independent of the cultivation method. Reversion to rangeland, both with and without N addition, resulted in lower N_2O emissions compared to the baseline winter wheat/fallow system. Across management alternatives, from 1-3% of the applied N fertilizer was lost as N_2O gas. The alternatives that did not involve irrigation (wwct, wwnt, rg, rg + N) showed no significant amounts of NO_3^- leaching (Figure 5.7c). However, 3 to 6% of the applied N fertilizer was leached from the irrigated corn, corn alfalfa, and silage crops.

To summarize the results and compare scenarios we aggregated the output for system C (SOM C + surface organic matter C + litter C), N_2O emissions, NO_3^- leaching, and crop yields into 25 year periods. Figure 8a shows the change in system C for each scenario from the perspective of the atmosphere. Thus, conversion from winter wheat/fallow rotations to continuous, irrigated corn cropping resulted in an increase of ~1700 gC m^{-2} in SOM during the first 25 year period after conversion with the C supplied by atmospheric CO_2. This indicates that C inputs from root senescence and surface litter supplied the SOM pool at a faster rate than decomposition depleted SOM by respiring it as CO_2. Conventional tillage winter wheat/fallow cropping showed no significant change in SOM because that system had been in place for a sufficient time period such that SOM had reached an equilibrium. The no tillage management option for winter wheat/fallow copping sequestered only small amounts of CO_2-C in SOM. However, conversion to perennial cropping and increased N or organic matter addition (the corn, corn/alfalfa and silage options) resulted in large increases in SOM, particularly during the first 25 year period following conversion. Range grass amended with N also showed significant increases in SOM.

Figure 5.8b shows that the corn and corn/alfalfa alternatives, which stored large amounts of CO_2-C in the soil, also emitted comparatively large amounts of N_2O as a result of N fertilizer application. However, the silage treatment that included manure addition also stored a large amount of C in SOM but emitted only slightly more N_2O than the wheat/fallow system. Range grass amended with N emitted more N_2O than the non-fertilized range grass, but still significantly less N_2O than the baseline winter wheat/fallow system. For the alternatives that sequestered C on the soil, N_2O emissions tended to increase with time as SOM levels began to stabilize and soil N levels increased.

Figure 5.8c shows net C sequestration for each scenario by accounting for flows of CO_2 between the atmosphere and the soil (Figure 8a), the CO_2 equivalents of N_2O emissions (Figure 8b), and the CO_2 costs of N fertilizer production. Winter wheat/fallow rotations showed a net input of greenhouse gases to the atmosphere under both conventional and no tillage cultivation except that the no till option stored a small amount of net C during the first 25 year period. The systems that use high N fertilizer inputs (corn and corn/alfalfa) showed large amounts of net C sequestration during the first 25 years after conversion but increases in SOM quickly diminished while N_2O emissions increased so that after 50-75 years these systems became net emitters of greenhouse gases. Conversion to silage showed net C uptake during the entire 100-year simulation. Reversion to rangeland accompanied with the addition of a small amount of N ($1\ g\ N\ m^{-2}$) also resulted in long term net C sequestration. Figure 5.8d shows the cumulative above ground NPP for the land use options. As expected, plant growth increased with N inputs and irrigation. Yields for winter wheat were not significantly affected by cultivation method. Addition of N to range grass resulted in an increase in NPP by about a factor of 2 compared to non-fertilized range grass. This increase in NPP accounts for the higher SOM simulated for the rg + N treatment (Figure 7a) and indicates that these soils are strongly N limited. Although N addition to the range grass resulted in higher N_2O emissions than the non-fertilized range grass, the increase in soil C storage more than compensates for this from the net greenhouse gas perspective.

Simulations of conventional till and no till corn and corn/soybean cropping

Corn and soybeans are major crops in the Midwestern region of the U.S. To compare the effects of tillage practice on soil C levels, N_2O emissions, crop yields, and NO_3^- leaching we first performed a 100 year simulation to derive initial conditions for soil C and nutrient levels. We used a weather file for Lafayette, Indiana (mean annual precipitation = 94 cm, mean annual temperature = 10.2 °C) and simulated traditional land use for a loam soil from this region. Corn/winter wheat/grass clover pasture rotations were simulated from 1880 to 1950. In 1951 the rotation was changed to corn/soybean/winter wheat/grass clover pasture. Chemical fertilizer was added beginning in 1951 and crop parameters were altered to reflect improved varieties of corn that were introduced. Starting in 1980, the cropping scheme was changed to one of four alternatives; conventional till perennial corn cropping (cct), no till perennial corn (cnt), conventional till corn/soybean rotations (cbct), and no till corn/soybean rotations (cbnt) as shown in Table 1. Fertilizer (ammonium nitrate) was added at a rate of 15 g N m^{-2} in a split application (7.5 g N m^{-2} in May and 7.5 g N m^{-2} in June) each year that corn was grown. Simulations were run until 2010 and output files were compiled for SOM, N_2O emissions, grain yields, and NO_3^- leaching.

DAYCENT simulations showed SOM decreasing from 1880 levels and reaching a minimum value of ~4000 gC m^{-2} in 1950. Soil C then increased to ~ 5000 gC m^{-2} in 1980 as a result of N fertilization. This is similar to the historical soil C data for some soils in the U.S. corn belt (Lal et al., 1998; Huggins et al., 1998). Figure 5.9a shows the changes in the base soil C level (1980 value) simulated for corn cropping under conventional tillage (cct), no till corn cropping (cnt), corn/soybean rotations under conventional tillage (cbct), and no till corn/soybean rotations (cbnt). Continuous corn cropping tends to store more C in the soil than corn/soybean rotations and no till cultivation results in higher C storage for both cropping alternatives. No till cultivation reduces N_2O emissions slightly and NO_3^- leaching significantly (Figures 5.9b, 5.9c). Less N is leached under no till because more N is retained in SOM that is not susceptible to leaching. Model results suggest that no till has benefits from both net greenhouse gas emission and NO_3 leaching perspectives.

To summarize and compare the results, we aggregated changes SOM, total C equivalents for N_2O emissions, and grain yields for 10 year periods. Figure 5.10a shows that C sequestration in soil diminishes with time as SOM approaches an equilibrium and that no till enhances soil C storage. Soil N_2O emissions show less dramatic differences among the treatments but no till tends to decrease N_2O emissions (Figure 5.10b). Corn/soybean rotations emitted less N_2O than continuous corn cropping because N fertilizer was not added during the soybean year. Net C (Figure 10c) was calculated by summing the change in system C (Figure 10a), the C equivalents of the aggregated N_2O emissions (Figure 5.10b), and the CO_2 costs associated with N fertilizer production. Both no till treatments (cnt, cbnt) showed net C sequestration for the first 10 year period, were essentially C neutral during the second 10 year period, and became net C emitters during the third 10 year period. The crops that were conventionally tilled were net emitters of C during each 10 year period. Tillage practice did not significantly affect grain yield

(Figure 5.10d). Corn has a higher growth rate than soybeans and produces a larger grain yield than soybeans (Figure 5.10d). Higher NPP for corn implies more C inputs to the soil so SOM values for a given tillage practice are higher for perennial corn cropping compared to corn soybean rotations (Figure 5.10a). To summarize, DAYCENT simulations suggest that conversion to no till in the U.S. cornbelt would have a minor effect on N_2O emissions but would significantly increase soil C and decrease NO_3^- leaching while maintaining high crop yields.

Discussion

We used a well validated ecosystem model to compare the effects of land management on SOM, N_2O emissions, plant production, and NO_3^- leaching for a Great plains soil that has been used for winter wheat fallow rotations and for a Midwestern soil used for corn/winter wheat/pasture rotations. In both cases, we first performed 100-year simulations to initialize SOM and soil nutrient levels. Model results support observations of previous researchers (Huggins et al. 1998; Paustian et al. 1997) that crop fallow rotations and conventional tillage can significantly reduce SOM. The established equilibrium soil C value for the Great Plains soil (1.3 kgC m^{-2}) was somewhat less than the value for the Midwestern soil (5.0 kgC m^{-2}). Both of these values are supported by data from the respective regions and the differences in base SOM levels are related to soil texture, precipitation, and historical cropping practices. The Midwestern soil we chose for simulations was finer textured so SOM was more likely to become stabilized than SOM in the coarser textured Great Plains soil that we used for simulations. The Midwestern soil also receives ~2.5 times the precipitation of the Great Plain soil. Higher precipitation implies more plant growth and a higher rate of input to the SOM pool. The Midwestern soil was historically cropped perennially whereas the Great Plains soil was used for crop/fallow rotations. During the fallow season, inputs from plant growth to the SOM and litter pools are highly reduced, but decomposition continues so SOM decreases during the fallow year. Perennial cropping supplies inputs to the SOM and litter pools every year and leads to higher SOM levels.

Results from both regions show that some types of agriculture can dramatically reduce soil C levels from what they were in the native condition and that this loss can be reversed by perennial cropping, N fertilization, irrigation, organic matter additions, no till cultivation and reversion to the native condition. However, the increase in SOM induced by N additions is partially offset by the associated increase in N_2O emissions and NO_3^- leaching. The potential to obtain net C sequestration in a soil after accounting for the CO_2 equivalent costs of N_2O emissions and N fertilizer production is related to the extent that the soil is depleted in SOM initially. Soils that are somewhat to highly depleted in SOM have the potential to sequester C in the short to intermediate term (10-50 years) upon changing management. Given that most agricultural systems will not be returned to the native condition and that N fertilizer and organic matter are already routinely added to cropped soils, perennial cropping rather than crop/fallow rotations and no till cultivation have the most potential to sequester C in these systems.

Crop/fallow rotations are disadvantageous for two reasons. During the fallow season SOM decreases and N_2O emissions are high. SOM decreases because inputs to SOM are greatly reduced but decomposition continues. N_2O emissions are high because soil water is higher and nitrifying microbes face little competition from plant growth for available NH_4^+ during the fallow season. Another factor that contributes to higher N_2O emissions during the fallow season with winter wheat cropping is that the cropping season includes the winter months when N_2O emissions tend to be low. Although the crop/fallow system is necessary for extremely dry regions, the range of precipitation levels that can support continuous cropping is expanded upon conversion to no till cultivation because no till conserves soil moisture. Under no till, soils take more time to warm up during the spring and soil aggregate structure is maintained so less water is evaporated. Great Plains soils that are highly depleted of SOM related to crop/fallow rotations could store large amount of C upon conversion to intensive, perennial cropping provided water for irrigation were made available.

The effect of the no till alternative was much stronger in the Midwestern soil compared to the great plains soil. Conventional tillage results in decreased SOM because the aggregate structure of the soil is altered, aggregate turnover is increased, and aggregate formation is decreased so SOM is less protected from decomposition (Six et al., 1999). The Midwestern soil was perennially cropped and the increase in SOM decomposition rate induced by plowing resulted in lower SOM compared to the no till practice. The Great Plains soil was not sensitive to cultivation style because of the crop/fallow rotation schedule used in this region. Plowing during the cropping year increases decomposition compared to no till for that year. But during the fallow year there is very little input to the SOM and litter pools, so that labile organic matter that was added to the system the previous year has sufficient time to decompose before the next cropping season, regardless of tillage practice. Similar to observations reported by Robertson et al. (in press), DAYCENT simulations suggest that no till has a small effect on N_2O emissions but a significant effect on SOM levels. To summarize, continuous cropping and N additions increase soil C because inputs to SOM are increased to a greater extent than decomposition. No till cultivation is not likely to lead to increased soil C sequestration under two year crop/fallow rotation schedules but will increase soil C for perennially cropped systems and for crop/fallow systems if the increase in soil moisture as a result of no till allows the proportion of fallow years in the rotation schedule to be reduced.

NO_3^- leaching from the irrigated corn and corn/alfalfa crops was higher for the Great Plains soil than for similar cropping in the Midwestern soil. This can be explained by soil textural differences. The Great Plains soil we simulated was a sandy loam and hence had a relatively high saturated hydraulic conductivity (K_{sat}) parameter. This facilitates movement of water through the soil profile and NO_3^- leaching. The simulated Midwestern soil was much finer textured, K_{sat} was lower, and less water was lost from the bottom of the profile so NO_3^- leaching was reduced. Although annual precipitation for the simulated Midwestern soil was ~2.5 times that of the Great Plains soil, enough water was added from irrigation of the corn and corn/soybean Great Plains scenarios such that total water inputs for these options were roughly equivalent to those of the Midwestern soil. Model results suggest that no till can reduce NO_3^- leaching in some soils but we not aware of any experimental evidence to support this assertion. The increase in soil water content associated with no till would tend to increase leaching but the increased N immobilization as a result of no till more than compensates for this in the simulated Great Plains soil.

DAYCENT simulations suggest that soils that are depleted in SOM can temporarily compensate for greenhouse gas emissions by changing land management. Although net carbon sequestration will not continue for more than 10-50 years, from the perspective of the net greenhouse gas emissions emitted by the conventional tillage crop/fallow and perennial cropping systems, the benefits of no till extend at least 100 years into the future. No till should not reduce crop yields and may reduce NO_3^- leaching, thus providing additional societal benefits.

Tables

Table 5.1. Land management practices simulated by DAYCENT

	Great Plains Soil			
Crop/Vegetation	N addition ($gN\ m^{-2}\ yr^{-1}$)	Month(s) of N addition	Irrigation	Tillage
winter wheat/fallow (wwct)	2.5	9,4	no	conventional
winter wheat/fallow (wwnt)	2.5	9,4	no	no till
corn	10	5,7	yes	conventional
corn/alfalfa (corn/alf)	6.3	5,7	yes	conventional
silage	6.25[m]	12	yes	conventional
range grass (rg)[g]	0		no	none
range grass (rg+N)[g]	1	6	no	none
	Midwestern Soil			
corn (cct)	15	5,6	no	conventional
corn (cnt)	15	5.6	no	no till
corn/soybean (cbct)	7.5	5,6	no	conventional
corn/soybean (cbnt)	7.5	5,6	no	no till

wwct = winter wheat/fallow rotations, conventional till
wwnt = winter wheat/fallow rotations, no till
corn = perennial corn cropping, conventional till
corn/alf = corn/alfalfa rotations, conventional till
silage = perennial silage cropping, conventional till
rg = native range grass
rg + N = native range grass amended with fertilizer
cct = perennial corn, conventional till
ccnt = perennial corn, no till
cbct = corn/soybean rotations, conventional till
cbnt = corn/soybean rotations, no till
[g] = grazed from April-November
[m] = N from manure, all others from ammonium nitrate fertilizer

References

Alexandrov, G.A., T. Oikawa, and G. Esser, 1999, Estimating terrestrial NPP: what the data say and how they may be interpreted?, *Ecological Modeling, 117*, 361-269.

Bruce, J.B., M. Frome, E. Haites, H. Janzen,R. Lal and K. Paustian, 1999, Carbon sequestration in soils, *Journal of Soil and Water Conservation, 54*, 382-389.

Bumb, B.L., and C.A. Baanante, 1996, The role of fertilizer in sustaining food security and protecting the environment to 2020. *Food, Agriculture, and the Environment Discussion Paper 17.* International Food Policy Research Institute. Washington, D.C. USA. 54 pp.

Conrad, R., 1996, Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO), *Microbiol. Rev., 60*, 609-640.

Davidson, E.A., 1992, Sources of nitric oxide and nitrous oxide following the wetting of dry soil, *Soil Science Society of America Journal, 56*, 95-102.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, D.S. Ojima, and M.D. Hartman, 2000, Interaction of soil carbon sequestration and N_2O flux with different land use practices, in J. van Ham et al. (eds), *Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation*, pp 303-311, Kluwer Academic Publishers, The Netherlands.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, D.S. Ojima, A.E. Kulmala and S. Phongpan, General model for N_2O and N_2 gas emissions from soils due to denitrification, in press, *Global Biogeochem. Cycles.*

Eitzinger, J., W.J. Parton, and M.D. Hartman, Improvement and validation of a daily soil temperature submodel for freezing/thawing periods, in press *Soil Science.*

Frolking, S.E., A.R. Mosier, D.S. Ojima, C. Li., W.J. Parton, C.S. Potter, E. Priesack, R. Stenger, C. Haberbosch, P. Dörsch, H. Flessa and K.A. Smith, 1998, Comparison of N_2O emissions from soils at three temperate agricultural sites: simulations of year round measurements by four models, *Nutrient Cycling in Agroecosystems, 52,* 77-105.

Galloway, J.N., W.H. Schlesinger, H. Levy II, A. Michaels, and J.L. Schnoor, 1995, Nitrogen fixation: Anthropogenic enhancement-environmental response, *Global Biogeochem. Cyc., 9,* 235-252.

Granli, T., and O.C. Bockman, 1994, Nitrous oxide from agriculture, *Nor. J. Agric. Sci (Suppl. 12),* 1-128.

Grant R F., N.G. Juma and W.B. McGill, 1993, Simulation of carbon and nitrogen transformations in soils, I, Mineralization, *Soil Biology & Biochemistry, 25,* 1317-1329.

Grant, R.F., and E. Pattey, 1999, Mathematical modeling of nitrous oxide emissions from an agricultural field during spring thaw, *Global Boigeochem. Cycles, 13*, 679-694.

Huggins, D.R., G.A. Buyanovsky, G.H. Wagner J.R. Brown, R.G. Darmody, T.R Peck, G.W. Lesoing M.B. Vanotti, and L.G. Bundy, 1998, Soil organic C in the tallgrass prairie-derived region of the corn belt: Effects of long-term crop management, *Soil Tillage & Research, 47*, 219-234.

Hutchinson, G.L., G.P. Livingston and E.A. Brams, 1993, Nitric and nitrous oxide evolution from managed subtropical grassland, in *Biogeochemistry of Global Change: Radiatively Active Trace Gases,* edited by R.S. Oremland, pp. 290-316, Chapman & Hall, New York.

Kelly, R.H., W.J. Parton, M.D. Hartman, L.K. Stretch, D.S. Ojima and D.S. Schimel, 1997, Intra and interannual variability of ecosystem processes in shortgrass steppe: New model, verification, simulations, in press, *Journal of Geophysical Research: Atmospheres.*

Kelly, R.H., W.J. Parton, G.L. Crocker, P.R. Grace, J. Klir, M. Korschens, P.R. Poulton and D.D. Richter, 1997, Simulating trends in soil organic carbon using the century model, *Geoderma 81*, 77-90.

Lal, R., J.M. Kimble, R.F. Follett and C.V. Cole, 1998, *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect*, Ann Arbor Press, Chelsea, MI.

Lieth, H., 1975, Modeling the primary productivity of the world, in H. Lieth and R. Whittaker (eds.) *Primary Productivity of the Biosphere*, Springer-Verlag, New York.

Martin, R.E., M.C. Scholes, A.R. Mosier, D.S. Ojima, E.A. Holland, and W.J. Parton, 1998, Controls on annual emissions of nitric oxide from soils of the Colorado shortgrass steppe, *Global Biogeochem. Cycles, 12*, 81-91.

Matson, P.A., and R.C. Harriss, 1995, Trace gas exchange in an ecosystem context: Multiple approaches to measurement and Analysis, in Biogenic *Trace Gases: Measuring Emissions from Soil and Water,* edited by P.A. Matson and R.C. Harriss, pp. 1-13, Blackwell Sci., Malden, Mass.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton, 1993, *CENTURY soil organic matter model environment*, Technical documentation, Agroecosystem version 4.0, Great Plains System Research Unit Technical Report No. 4, USDA-

ARS, Fort Collins, Colorado.

Mosier, A.R., W.D. Guenzi, and E.E. Schweizer, 1986, Soil losses of dinitrogen and nitrous oxide from irrigated crops in northeastern Colorado, *Soil Science Society of America Journal, 50*, 344-348.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel, and J.A. Delgado, 1996, CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 1. Impact of landscape and nitrogen addition, *Global Biogeochem. Cycles, 10*, 387-399.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel, and O. Hienemeyer, 1997, CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change, *Global Biogeochem. Cycles, 11*, 29-42.

Nuttle, W.K., 2000, Ecosystem managers can learn from past successes, *EOS, 81*, 278.

Parton, W.J., 1978, Abiotic section of ELM, in G.S. Innis (ed.) *Grassland Simulation Model, Ecological Studies Analysis and Synthesis, 45*, pp 31-53.

Parton, W.J., 1984, Predicting soil temperatures in a shortgrass steppe, *Soil Science, 138*, 93-101.

Parton, W. J., and P. E. Rasmussen, 1994, Long-term effects of crop management in wheat/fallow: II. CENTURY model simulations, *Soil Science Society of America Journal, 58*, 530-536.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.J. Scholes, D.S. Schimel, T. Kirchner, J.C. Menaut, T. Seastedt. E. Garcia Moya, Apinan Kamnalrut, and J.L. Kinyamario, 1993, Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide, *Global Biogeochem. Cycles*, 7, 785-809.

Parton, W.J., D.S. Ojima, C.V. Cole and D.S. Schimel, 1994, A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. In: *Quantitative Modeling of Soil Forming Processes, SSSA, Spec. Pub. 39*, pp. 147-167, Madison, WI.

Parton, W.J., A.R. Mosier, D.S. Ojima, D.W. Valentine, D.S. Schimel, K. Weier, and K.E.

Kulmala, 1996, Generalized model for N_2 and N_2O production from nitrification and denitrification, *Global Biogeochemical Cycles, 10*, 401-412.

Parton, W.J., M. Hartman, D.S. Ojima and D.S. Schimel, 1998, DAYCENT: Its land surface submodel: description and testing, *Global Planetary Change, 19*, 35-48.

Parton, W.J., E.A. Holland, S.J. Del Grosso, M.D. Hartman, R.E. Martin, A. R. Mosier, D.S. Ojima and D.S. Schimel, Generalized Model for NO_x and N_2O Emissions from Soils, submitted to *journal of Geophysical Research: Atmospheres.*

Paustian, K., W.J. Parton and J. Persson, 1992, Modeling soil organic matter in organic amended and nitrogen-fertilized long term plots, *Soil Science Society of America Journal, 56*, 476-488.

Paustian, K., O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. Van Noordwijk, and P.L. Woomer, 1997, Agricultural soils as a sink to mitigate CO_2 emissions, *Soil Use & Management, 13*, 230-244.

Penman, H.L., 1948, Natural evaporation from open water, bare soil and grass, *Proc. R Soc. London, Ser. A. 193*, 120-145.

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka, 1998, Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C, *Soil Tillage & Research*, 47, 207-218.

Potter, C.S., E.A. Davidson, and L.V. Verchot, 1996, Estimation of global biogeochemical controls and seasonality in soil methane consumption, *Chemosphere, 32*, 2219-2245.

Prather, M, Derwent, R., Ehhalt, D., Fraser, P., Sanhueza, E., Zhou, X., 1995, Chapter 2, Other trace gases and atmospheric chemistry. In: Houghton, J.T., Meira Filho, L.G., Lee, J.B.H., Callander, B.A., Haites, E., Harris, N, Maskell, K. (Eds.). *Climate change 1994. Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*, Published for the Intergovernmetnal Panel on Climate Change, Cambridge University Press, p. 77-126.

Robertson, G.P., E.A. Paul, and R.R. Harwood, Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere, in press, *Science*.

Schlesinger, W.H., 1999, Carbon sequestration in soils, *Science 284*, 2095.

Six, J, E.T. Elliot, and K. Paustian, 1999, Aggregate and soil organic matter dynamics under conventional and no-tillage systems, *Soil Science Society of America Journal*, 63, 1350-1358.

Smart, D.R., J.M. Stark, and V. Diego, 1999, Resource limitation to nitric oxide emissions from a sagebrush-steppe ecosystem, *Biogeochem., 47*, 63-86.

Smil, V., 1999, Nitrogen in crop production: An account of global flows, *Global Biogeochemical Cycles, 13*, 647-662.

Vitousek, P.M., Aber, J., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H., Tilman, D.G., 1997, Human alteration of the global nitrogen cycle: causes and consequences, *Issues in Ecology, 1*, 1-15.

Yienger, J.J. and H. Levy, 1995, Empirical model of global soil biogenic NO_X emissions, *J. Geophys. Res., 100*, 11447-11464.

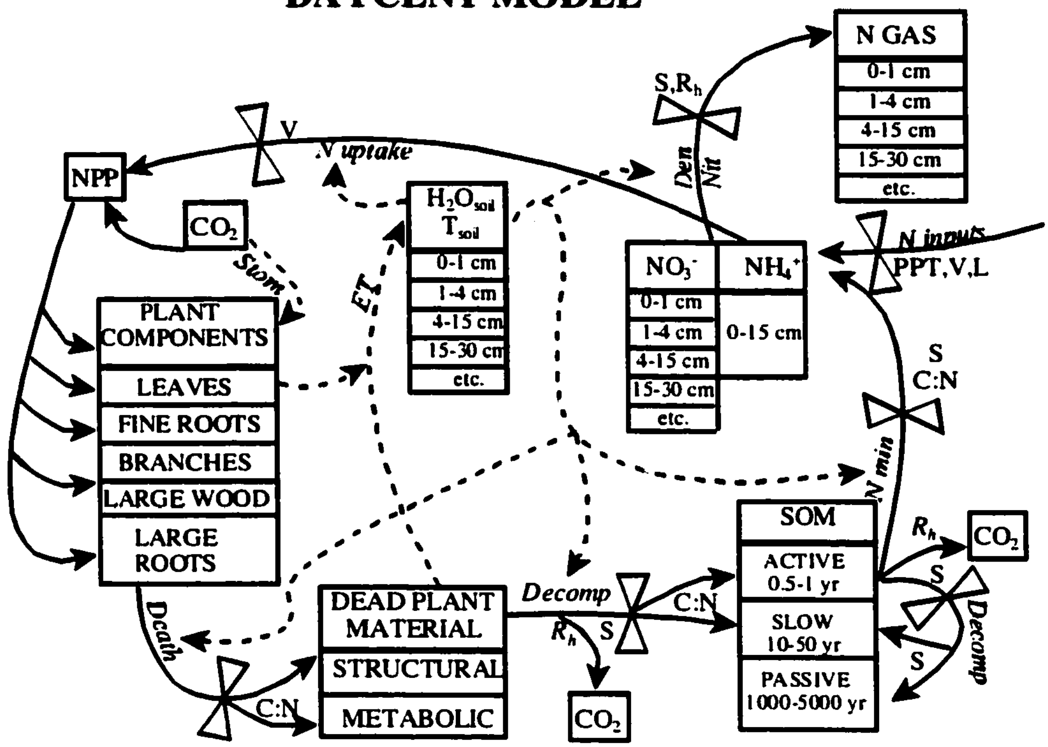
List of Figures

Figure 8. Summaries of DAYCENT simulations of changes in system C (a), cumulative CO_2-C equivalents of N_2O gas emissions (b), net C (c), and cumulative above ground plant productivity (d) for 25 year periods of conventional tillage winter wheat/fallow and 6 alternative land uses.

Figure 9. Simulated yearly changes in system C (soil C + litter C + surface organic matter C) (a), cumulative yearly N_2O emissions (b), and cumulative yearly NO_3^- leaching (c) for a Midwestern soil under conventional till and no till perennial corn and corn/soybean cropping.

Figure 10. Summaries of DAYCENT simulations of changes in system C (a), cumulative CO_2-C equivalents of N_2O gas emissions (b), net C (c), and cumulative above ground plant productivity (d) for 10 year periods of conventional till and no till perennial corn and corn/soy bean cropping.

DAYCENT MODEL



→ = C, N flows
- - → = Feedbacks, information flows
⋈ = Control on process
$H2O_{soil}$ = Soil water content
T_{soil} = Soil temperature
S = Soil texture
C:N = Carbon:Nitrogen ratio of material
V = Vegetation type
SOM = Soil Organic Matter
L = Land use
R_h = Heterotrophic respiration

N GAS = N_2O, NO_X, N_2
Processes designated by *italics*
Stom = Stomatal conductance
Death = Plant component death
Decomp = Decomposition
N inputs = N Fixation, N deposition, N fertilization
Nit = Nitrification
Den = Denitrification
N min = N mineralization
ET = Evapotranspiration

Figure 5.1

CROP/GRASS GROWTH SUBMODEL

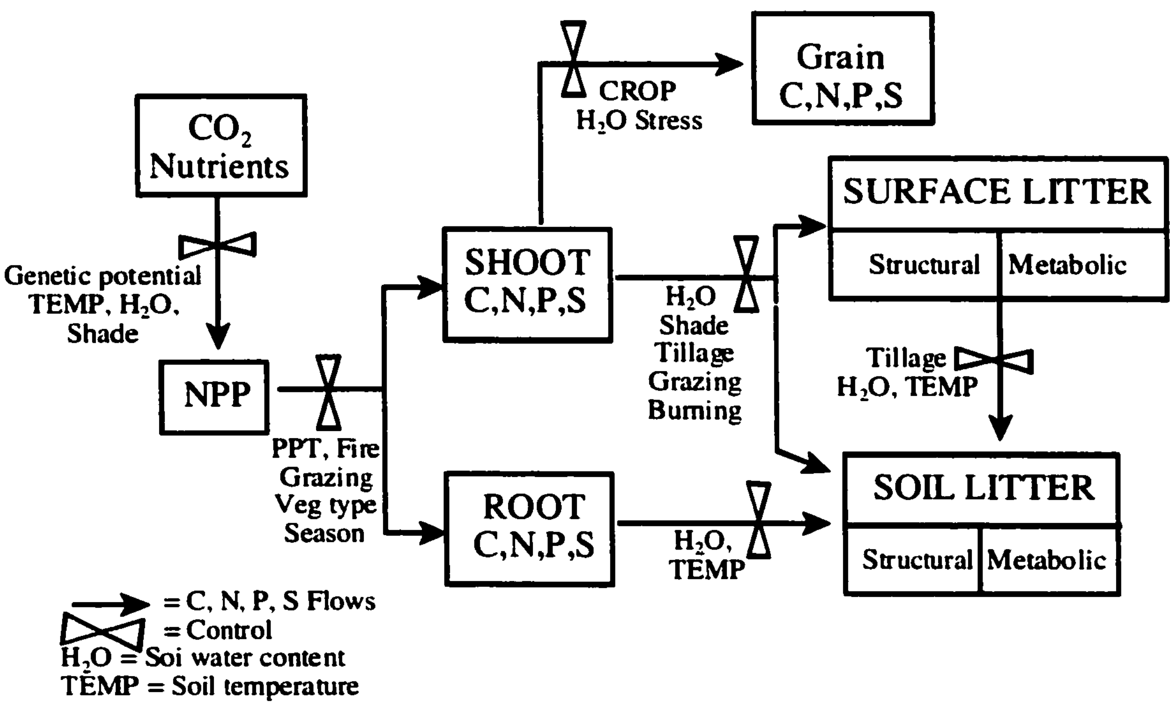


Figure 5.2

N Gas Submodel

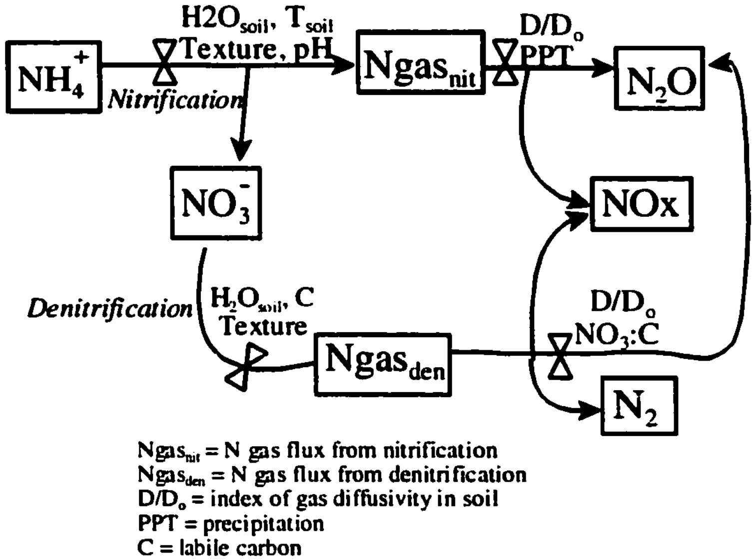


Figure 5.3

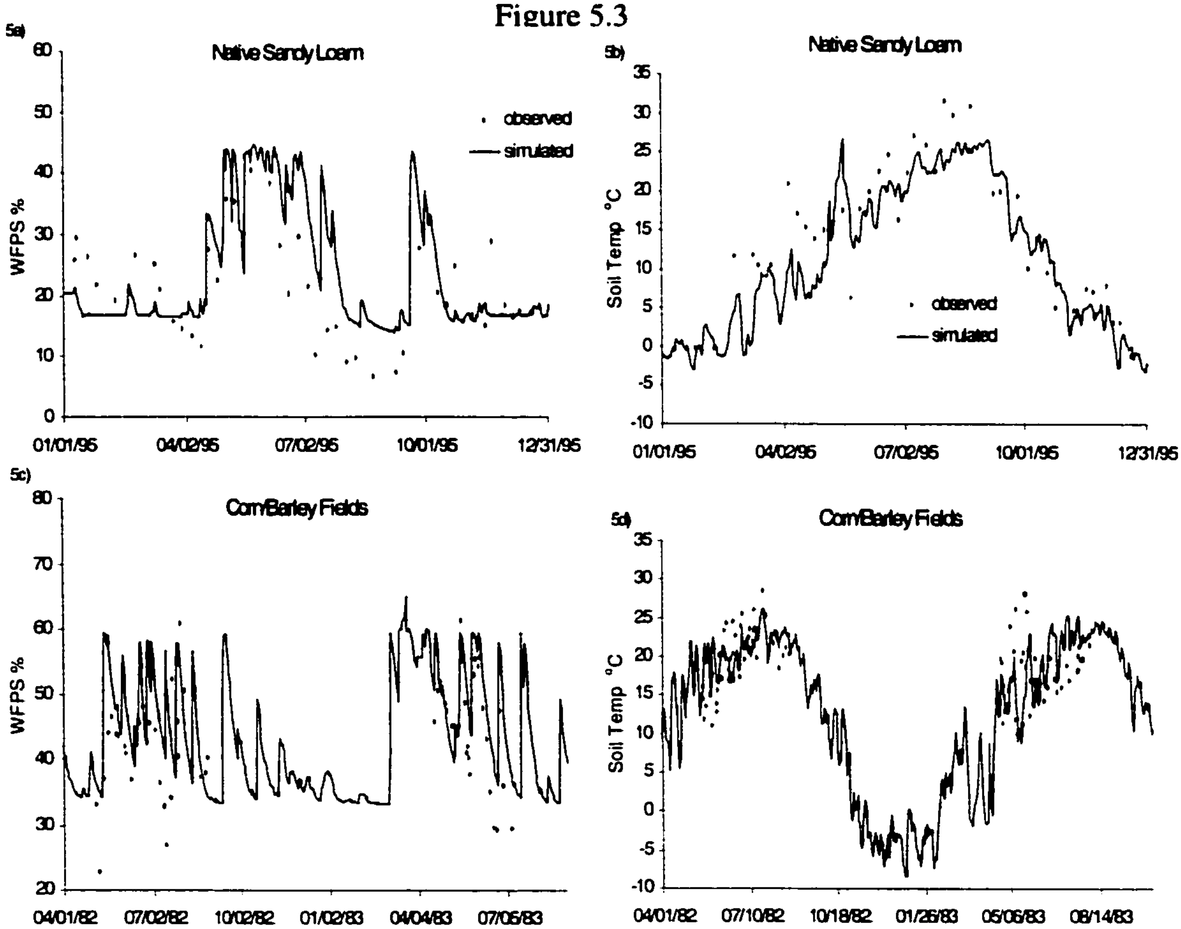
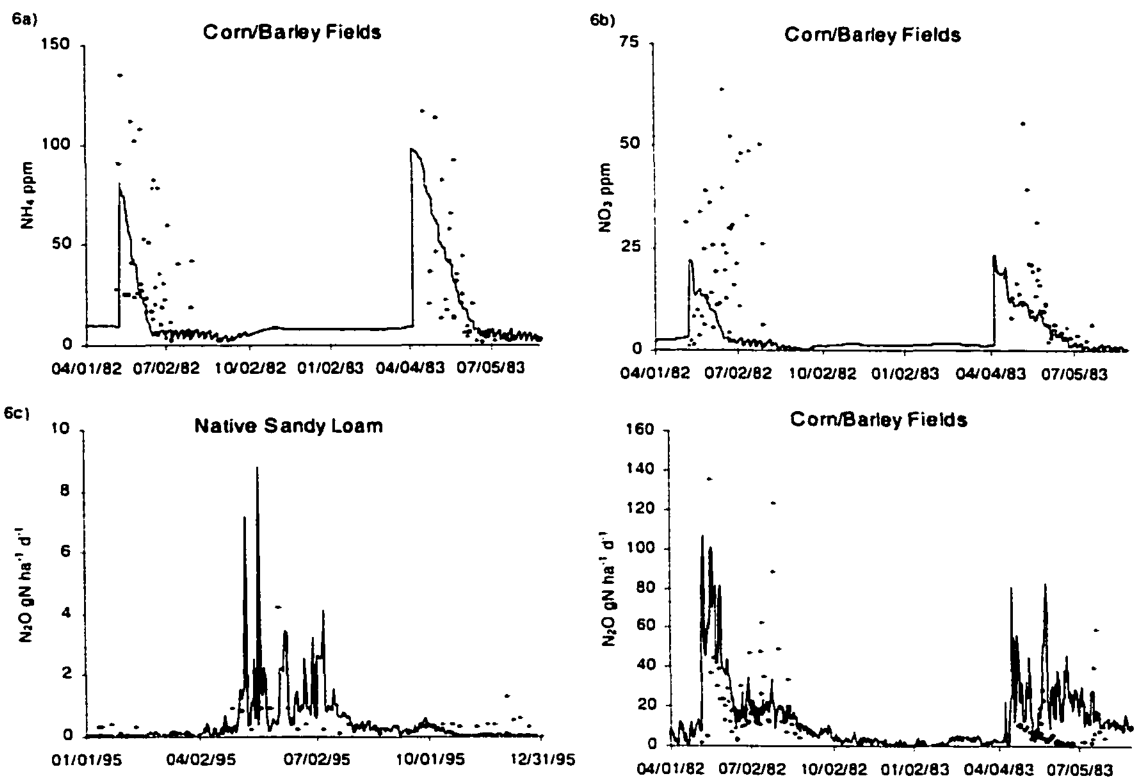


Figure 5.4



6a)
Corn/Barley Fields
NH4 ppm
150
100
50
0
04/01/82 07/02/82 10/02/82 01/02/83 04/04/83 07/05/83
6b)
Corn/Barley Fields
NO3 ppm
75
50
25
0
04/01/82 07/02/82 10/02/82 01/02/83 04/04/83 07/05/83
6c)
Native Sandy Loam
N2O gN ha-1 d-1
10
8
6
4
2
0
01/01/95 04/02/95 07/02/95 10/01/95 12/31/95
Corn/Barley Fields
N2O gN ha-1 d-1
160
140
120
100
80
60
40
20
0
04/01/82 07/02/82 10/02/82 01/02/83 04/04/83 07/05/83

Figure 5.6

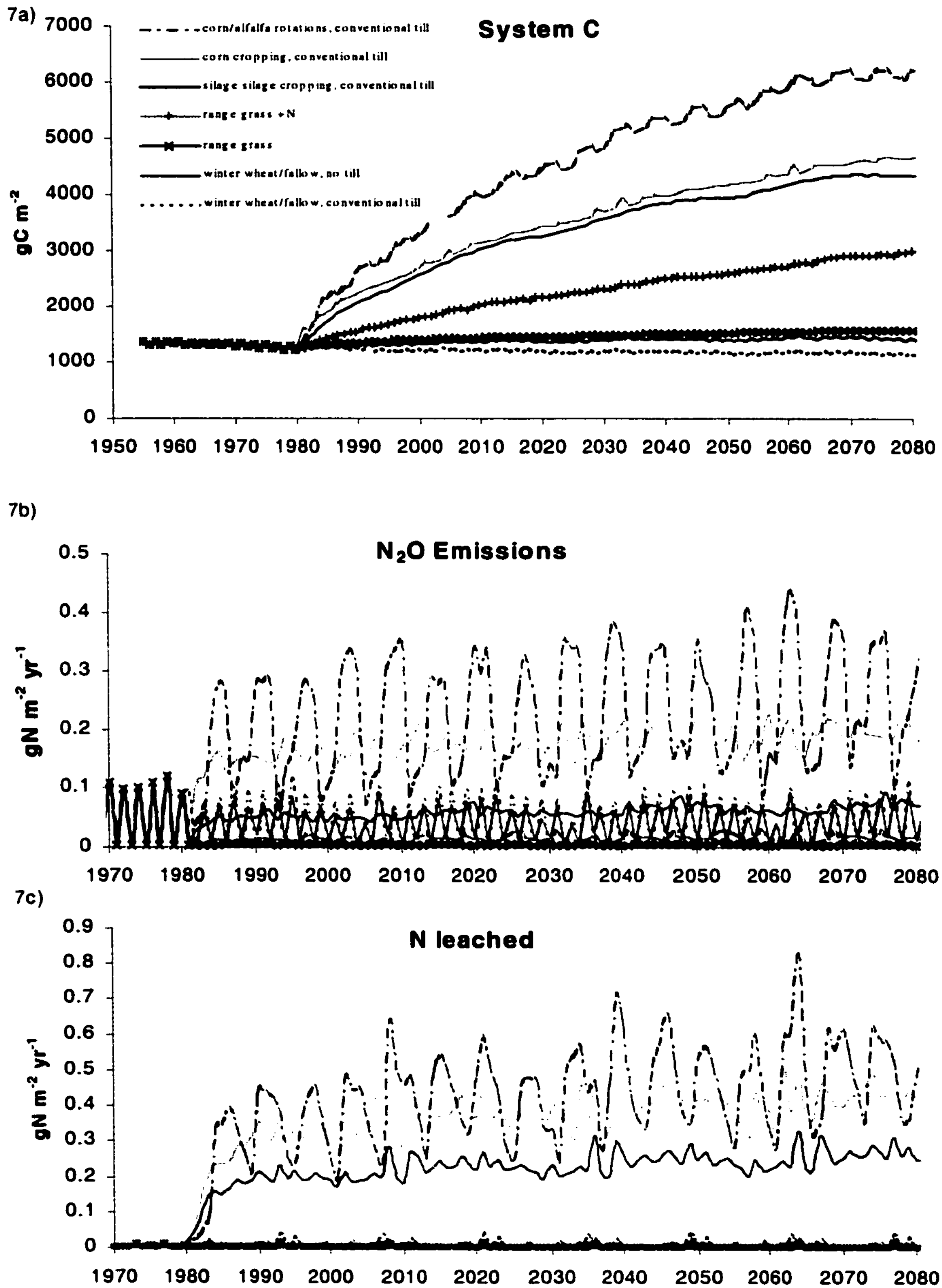

7a)
System C
corn/alfalfa rotations, conventional till
corn cropping, conventional till
silage silage cropping, conventional till
range grass +N
range grass
winter wheat/fallow, no till
winter wheat/fallow, conventional till
gC m-2
0
1000
2000
3000
4000
5000
6000
7000
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
7b)
N2O Emissions
gN m-2 yr-1
0
0.1
0.2
0.3
0.4
0.5
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
7c)
N leached
gN m-2 yr-1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080

Figure 5.7

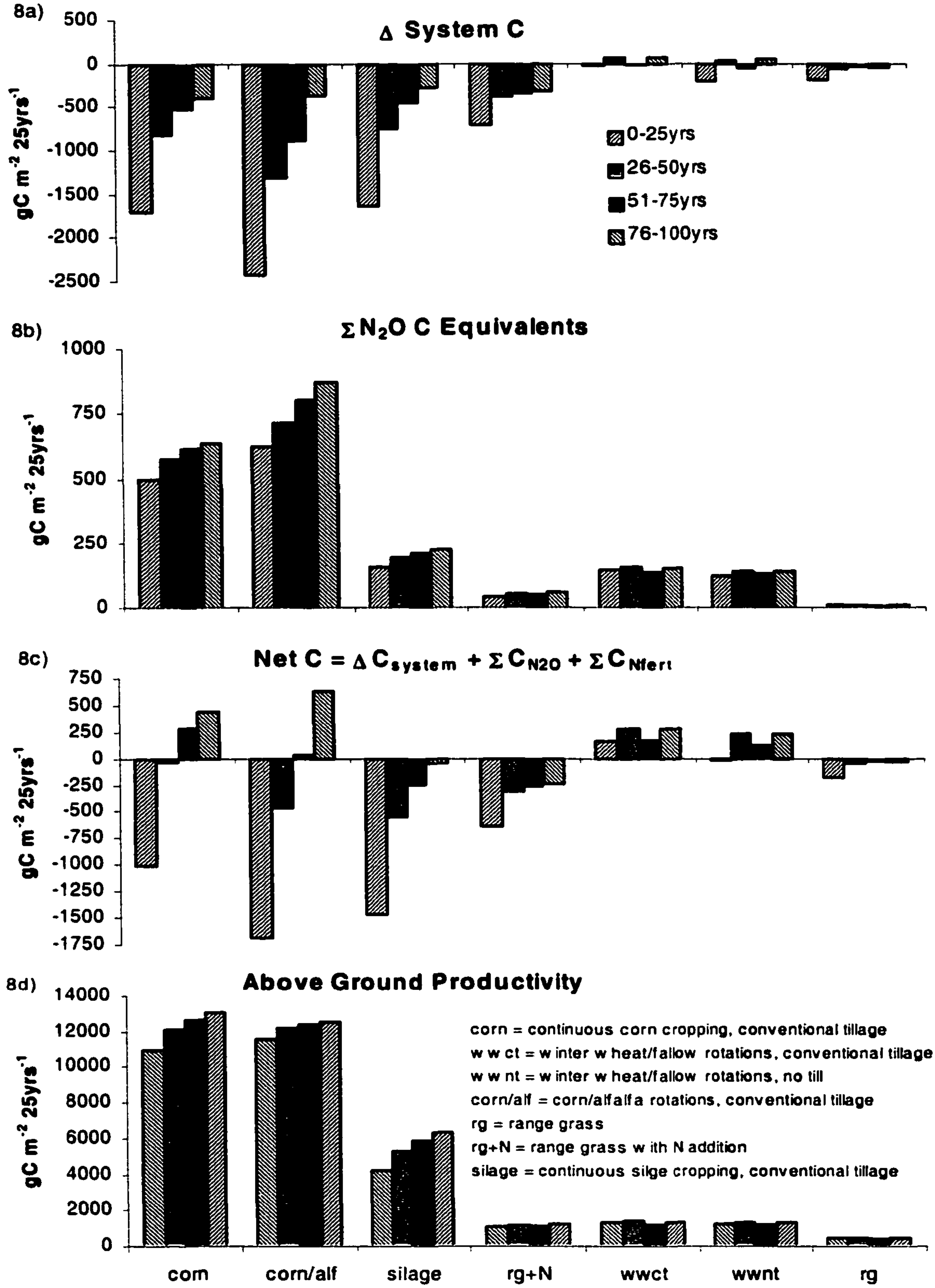

8a)
Δ System C
gC m^-2 25yrs^-1
500
0
-500
-1000
-1500
-2000
-2500
0-25yrs
26-50yrs
51-75yrs
76-100yrs
8b)
Σ N2O C Equivalents
gC m^-2 25yrs^-1
1000
750
500
250
0
8c)
Net C = Δ Csystem + Σ CN2O + Σ CNfert
gC m^-2 25yrs^-1
750
500
250
0
-250
-500
-750
-1000
-1250
-1500
-1750
8d)
Above Ground Productivity
gC m^-2 25yrs^-1
14000
12000
10000
8000
6000
4000
2000
0
corn = continuous corn cropping, conventional tillage
w w ct = w inter w heat/fallow rotations, conventional tillage
w w nt = w inter w heat/fallow rotations, no till
corn/alf = corn/alfalfa rotations, conventional tillage
rg = range grass
rg+N = range grass w ith N addition
silage = continuous silge cropping, conventional tillage
corn
corn/alf
silage
rg+N
wwct
wwnt
rg

Figure 5.8

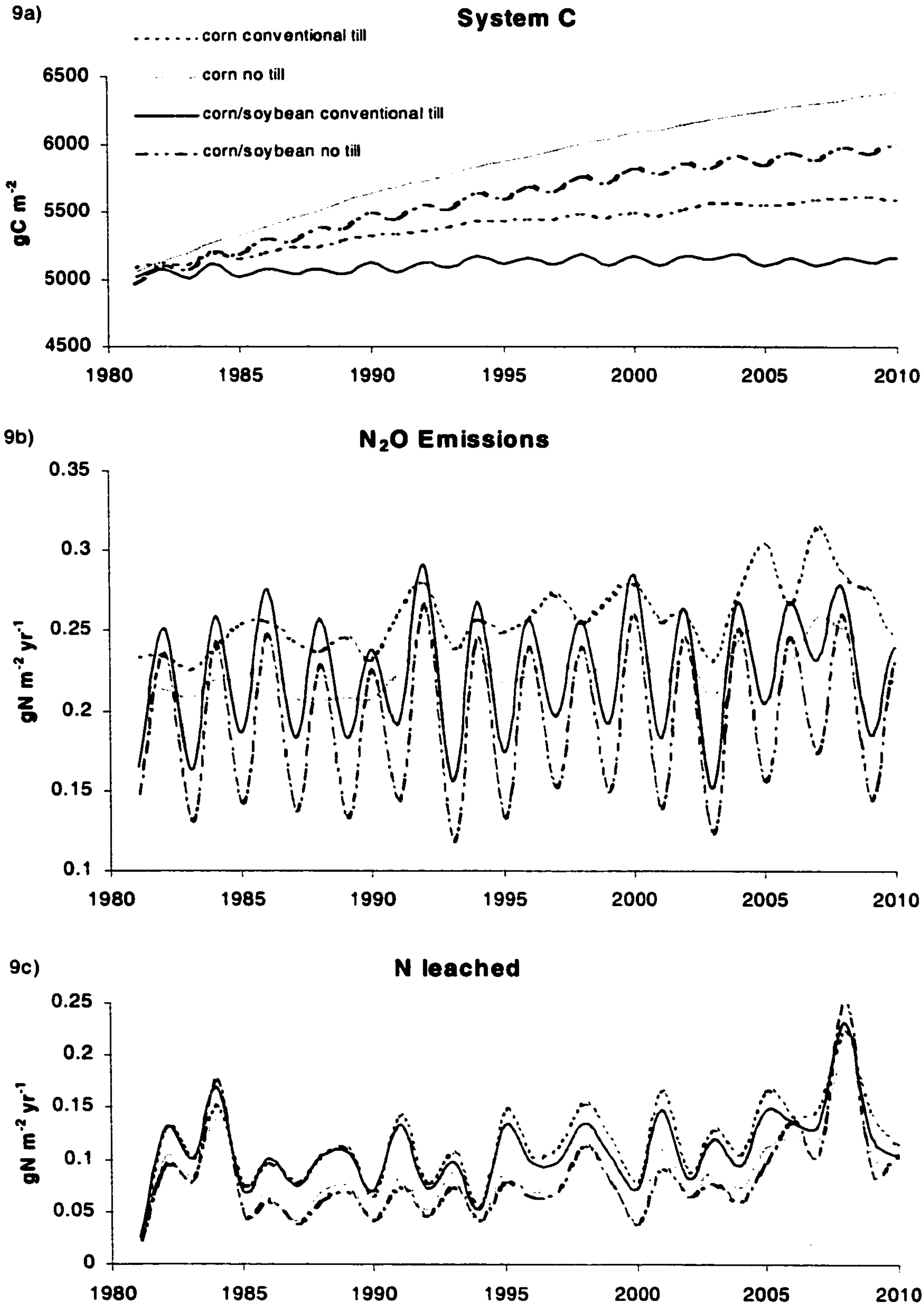
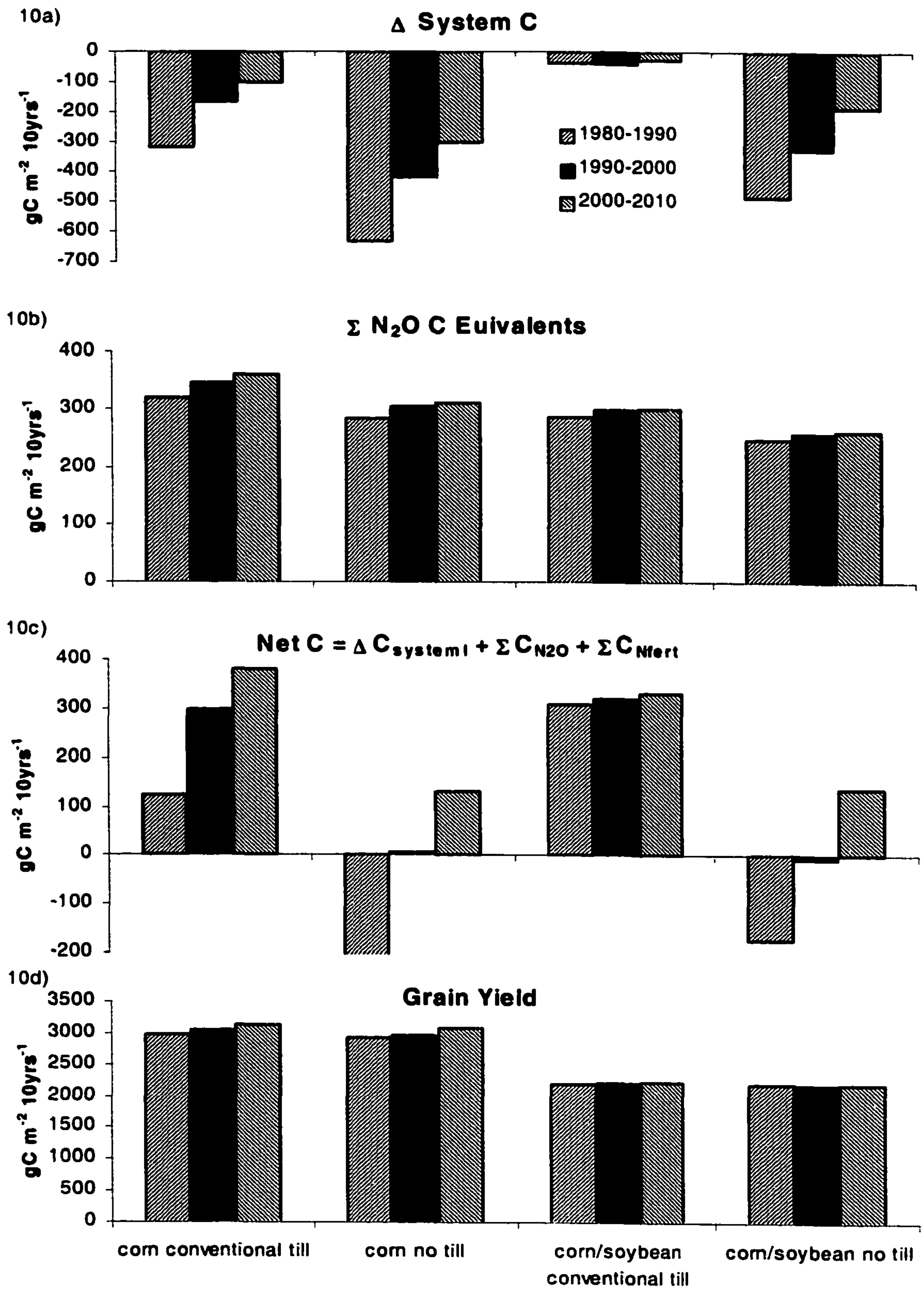

9a)
System C
corn conventional till
corn no till
corn/soybean conventional till
corn/soybean no till
gC m-2
6500
6000
5500
5000
4500
1980
1985
1990
1995
2000
2005
2010
9b)
N2O Emissions
gN m-2 yr-1
0.35
0.3
0.25
0.2
0.15
0.1
1980
1985
1990
1995
2000
2005
2010
9c)
N leached
gN m-2 yr-1
0.25
0.2
0.15
0.1
0.05
0
1980
1985
1990
1995
2000
2005
2010

Figure 5.9



10a)
Δ System C
0
-100
-200
-300
-400
-500
-600
-700
gC m-2 10yrs-1
1980-1990
1990-2000
2000-2010
10b)
Σ N2O C Euivalents
400
300
200
100
0
gC m-2 10yrs-1
10c)
Net C = Δ Csystem + Σ CN2O + Σ CNfert
400
300
200
100
0
-100
-200
gC m-2 10yrs-1
10d)
Grain Yield
3500
3000
2500
2000
1500
1000
500
0
gC m-2 10yrs-1
corn conventional till
corn no till
corn/soybean conventional till
corn/soybean no till

Figure 5.10

CHAPTER 6

SIMULATED EFFECTS OF DRYLAND CROPPING INTENSIFICATION ON SOM AND GREENHOUSE GAS EXCHANGES USING THE DAYCENT ECOSYSTEM MODEL

Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R., Peterson, G.A., Schimel, D.S., 2002. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. *Environmental Pollution* 116: S75-S83.

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.

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 (Huggins 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., 2000a). 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, 2000; 1999). 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 comparisons because the winter wheat/fallow system is commonly used in the central and southern U.S. 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.

Materials and Methods

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., 2000a). 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.

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., 2000a). 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 U.S. Great Plains soil used for winter wheat/fallow cropping and a Midwestern U.S. 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. ~47 cm, annual temp. ~9.6 °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 (Figure 6.1a). 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 (Figure 6.1b). 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 (Figure 1c). Although the model correctly simulated average trace gas emission rates for the different soils very well (Figures 1b, 1c), model performance on the daily time scale for particular soils was not as favorable. To demonstrate the variability in daily trace gas flux rates, figure 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 (Figure 6.2a). 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 (Figure 6.2b).

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 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).

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).

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 gN 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.

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 temp. ~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).

Figure 6.3a 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. Figure 6.3b 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 (Figure 6.3b). Winter wheat yielded similar amounts of grain when alternated with fallow or with annual summer crops (Figure 6.3b). 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 (Figure 6.3c). Simulated CH_4 uptake rates did not strongly differ among treatments, although the native grass absorbed slightly more CH_4 than the cropped soils (Figure 6.3c).

Figures 6.4a and 6.4b 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 C equivalents of CH_4 uptake are shown as negative values in Figure 6.4a 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 Figure 6.4b 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. Figure 6.4c 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 greenhouse gases to the atmosphere, annual cropping was a somewhat smaller net source, and the native grass provided a net sink.

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 (Huggins 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 (Figures 1a and 3a) and DAYCENT showed an annual net accumulation of 2-13 gC m^{-2} yr^{-1} upon conversion from conventional tillage winter wheat/fallow to either native grass, no till winter wheat/fallow, or no till annual cropping (Figure 6.4a). All of the land use alternatives in Figure 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 Figure 6.4a are for the first 12 years following conversion and C sequestration rates are expected to decrease as soils become C saturated (Del Grosso et al., 2000; Paustian et al. 1998).

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 (Figure 6.4b). 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 $gN_2O\text{-}N\ ha^{-1}\ yr^{-1}$) 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 (Figure 6.4a) 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 (Figure 6.4a) 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 (Robertson et al., 2000; Mosier et al., 1997). 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 (Figure 6.4c). Although native un-grazed 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 (Figure 6.4). 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 un-grazed 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 to 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 (Figure 6.1) 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 (Figure 6.3) 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.

Acknowledgements

The research for this paper was supported by the National Aeronautics and Space Administration, the National Science Foundation, the Department of Energy and the Environmental Protection Agency through the following grants; NASA-EOS NAGW 2662, NSF-LTER BSR9011659, DOE NIGEC LWT62-123-06516 and EPA Regional Assessment R824939-01-0.

References

Bronson, K.F., Mosier, A.R., 1994. Suppression of methane oxidation in aerobic soil by nitrogen fertilizers, nitrification inhibitors, and urease inhibitors. Biology and Fertility of Soils 17, 263-268.

Bruce, J.B., Frome, M., Haites, E., Janzen, H., Lal, R., Paustian, K., 1999. Carbon sequestration in soils. Journal of Soil and Water Conservation 54, 382-389.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S., Schimel, D.S., 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: Schaffer, M., Ma, L., and Hansen, S. (Eds.), Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Potter,C.S., Borken, W., Brumme, R., Butterbach-Bahl, K., Crill, P.M., Dobbie, K., Smith, K.A., 2000a. General CH_4 oxidation model and comparisons of CH_4 oxidation in natural and managed systems. Global Biogeochemical Cycles 14, 999-1019.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Kulmala, A.E., Phongpan, S., 2000b. General model for N_2O and N_2 gas emissions from soils due to denitrification. Global Biogeochemical Cycles 14, 1045-1060.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.D., Hartman, M.D., 2000c. Interaction of soil carbon sequestration and N_2O flux with different land use practices. In: van Ham, J., Baede, A.P.M., Meyer, L.A., Ybema, R. (Eds.), Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation. Kluwer Academic Publishers, The Netherlands, pp. 303-311.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Keough, C.A., Peterson, G.A., Ojima, D.S., Schimel, D.S., 2001. Simulated effects of land use, soil texture, and precipitation on N gas emissions using DAYCENT. In: Follett, R.F., Hatfield, J.L. (Eds.), Nitrogen in the Environment: Sources, Problems, and Management. Elsevier Science Publishers, The Netherlands, in press.

Doran, J.W., Elliot, E.T., Paustian, K., 1998. Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management. Soil Tillage & Research 49, 3-18.

Eitzinger, J., Parton, W.J., Hartman, M.D., 2000. Improvement and validation of a daily soil temperature submodel for freezing/thawing periods. Soil Science 165, 525-534.

Farahani, H.J., Peterson, G.A., Westfall, D.G., Sherrod, L.A., Ahuja, L.R., 1998. Soil water storage in dryland cropping systems: the significance of cropping intensification. Soil Science Society of America Journal 62, 984-991.

Frolking, S.E., Mosier, A.R., Ojima, Li., C., Parton, W.J., Potter, C.S., Priesack, E., Stenger, R., Haberbosch, C., Dörsch, P., Flessa, H., Smith, K.A., 1998. Comparison of N_2O emissions from soils at three temperate agricultural sites: simulations of year round measurements by four models, Nutrient Cycling in Agroecosystems 52, 77-105.

Halverson, A.D., Ruele, C.A, Follett, R.F., 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Science Society of America Journal 63, 912-917.

Huggins, D.R., Buyanovsky, G.A., Wagner, G.H., Brown, J.R, Darmody, T.R Peck, T.R., Lesoing, G.W., Vanotti, M.B., Bundy, L.G., 1998. Soil organic C in the tallgrass prairie-derived region of the corn belt: effects of long-term crop management. Soil Tillage & Research 47, 219-234.

Hutchinson, G.L., Livingston, G.P., Brams, E.A., 1993. Nitric and nitrous oxide evolution from managed subtropical grassland. In: Oremland, R.S. (Ed.), Biogeochemistry of Global Change: Radiatively Active Trace Gases. Chapman & Hall, New York, pp. 290-316.

Kelly, R.H., Parton, W.J., Hartman, M.D., Stretch, L.K., Ojima D.S., Schimel, D.S., 2000. Intra and interannual variability of ecosystem processes in shortgrass steppe. Journal of Geophysical Research: Atmospheres 105, 20,093-20,100.

Kessavalou, A., Doran, J.W., Mosier, A.R., and Drijber, R.A., 1998a. Greenhouse gas fluxes following tillage and wetting in a wheat-fallow cropping system. Journal of Environmental Qualilty 27, 1105-1116.

Kessavalou, A., Mosier, A.R., Doran, J.W., Drijber, R.A., Lyon, D.L., Heinemeyer, O., 1998b. Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. Journal of Environmental Quality 27, 1094-1104.

Lal, R., Kimble, J.M., Follett R.F., Cole, C.V., 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Ann Arbor Press, Chelsea, MI.

Martin, R.E., Scholes, M.C., Mosier, A.R., Ojima, D.S., Holland, E.A., Parton, W.J., 1998. Controls on annual emissions of nitric oxide from soils of the Colorado shortgrass steppe. Global Biogeochemical Cycles 12, 81-91.

Metherell, A.K., Harding, L.S., Cole, C.V., Parton, W.J., 1993. CENTURY soil organic matter model environment, Technical documentation, Agroecosystem version 4.0. Great Plains System Research Unit Technical Report No. 4. USDA-ARS, Fort Collins, Colorado.

Mosier, A.R., Parton, W.J., Valentine, D.W., Ojima, D.S., Schimel, D.S., Hienemeyer, O., 1997. CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change. Global Biogeochemical Cycles 11, 29-42.

Ojima, D.S., Valentine, D.W., Mosier, A.R., Parton W.J., Schimel, D.S., 1993. Effect of land use change on methane oxidation in temperate forest and grassland soils. Chemosphere 26, 675-685.

Parton, W. J., Rasmussen, P.E., 1994. Long-term effects of crop management in wheat/fallow: II. CENTURY model simulations. Soil Science Society of America Journal 58, 530-536.

Parton, W.J., J.M.O. Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J.C., Seastedt, T., Garcia Moya, E., Kamnalrut, A., Kinyamario J.L., 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochemical Cycles 7, 785-809.

Parton, W.J., Ojima, D.S., Cole C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management.

In: Quantitative Modeling of Soil Forming Processes. Soil Science Society of America, Special Pub. 39, Madison, WI., pp. 147-167.

Parton, W.J., Hartman, M.D., Ojima, D.S., Schimel, D.S., 1998. DAYCENT: Its land surface submodel: description and testing. Global Planetary Change 19, 35-48.

Parton, W.J., Holland, E.A., Del Grosso, S.J., Hartman, M.D., Martin, R.E., Mosier, A.R., Ojima, D.S., Schimel, D.S. Generalized model for NO_x and N_2O emissions from soils. Journal of Geophysical Research: Atmospheres, in press.

Paustian, K., Cole, C.V., Sauerbeck, D., Sampson, N., 1998. CO_2 mitigation by agriculture: an overview. Climate Change 40, 135-162.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use & Management 13, 230-244.

Paustian, K., Parton W.J., Persson, J., 1992. Modeling soil organic matter in organic amended and nitrogen-fertilized long term plots. Soil Science Society of America Journal 56, 476-488.

Peterson, G.A., Halvorson, A.D., Havlin, J.L., Jones, O.R., Lyon, D.L., Tanaka, D.L., 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Tillage and Research 47, 207-218.

Peterson, G.A., Westfall, D.D., Peairs, F.B., Sherrod, L., Poss, D., Gangloff, W., Larson, K., Thompson, D.L., Ahuja, L.R., Koch, M.D., Walker, C.B., 2000. Sustainable dryland agroecosystem management, TB00-03. Colorado State University and Agricultural Experiment Station, Fort Collins, CO.

Prather, M.J., R.Derwent, R., D. Ehhalt, D., P. Fraser, P., E. Sanhueza, E.,and X. Zhou, X., 1995. Other trace gases and atmospheric chemistry. In: Houghton, J.T., Meira Filho, L.G., Lee, J.B.H., Callander, B.A., Haites, E., Harris, N, Maskell, K. (Eds.), Climate Change 1994. Cambridge University Press, Cambridge, UK, pp. 73-126.

Robertson, GP, Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 1922-1925.

Schlesinger, W. H., 2000. Carbon sequestration in soils: Some cautions amidst optimism. Agriculture Ecosystems & Environment 82, 121-127.

Schlesinger, W.H., 1999. Carbon sequestration in soils. Science 284, 2095.

Smart, D.R., Stark, J.M., Diego, V., 1999. Resource limitation to nitric oxide emissions from a sagebrush-steppe ecosystem. Biogeochemistry 47, 63-86.

Yienger, J.J., Levy, H., 1995. Empirical model of global soil biogenic NO_X emissions. Journal of Geophysical Research 100, 11447-11464.

List of Figures

Figure 6.1. 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.

Figure 6.2. 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).

Figure 6.3. 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.

Figure 6.4. a) Annual uptake of CO_2-C driven by changes in SOM C (C_{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 Figures 4a and 4b. Positive values represent emissions from the soil to the atmosphere while negative values represent uptake of atmospheric gas by the soil.

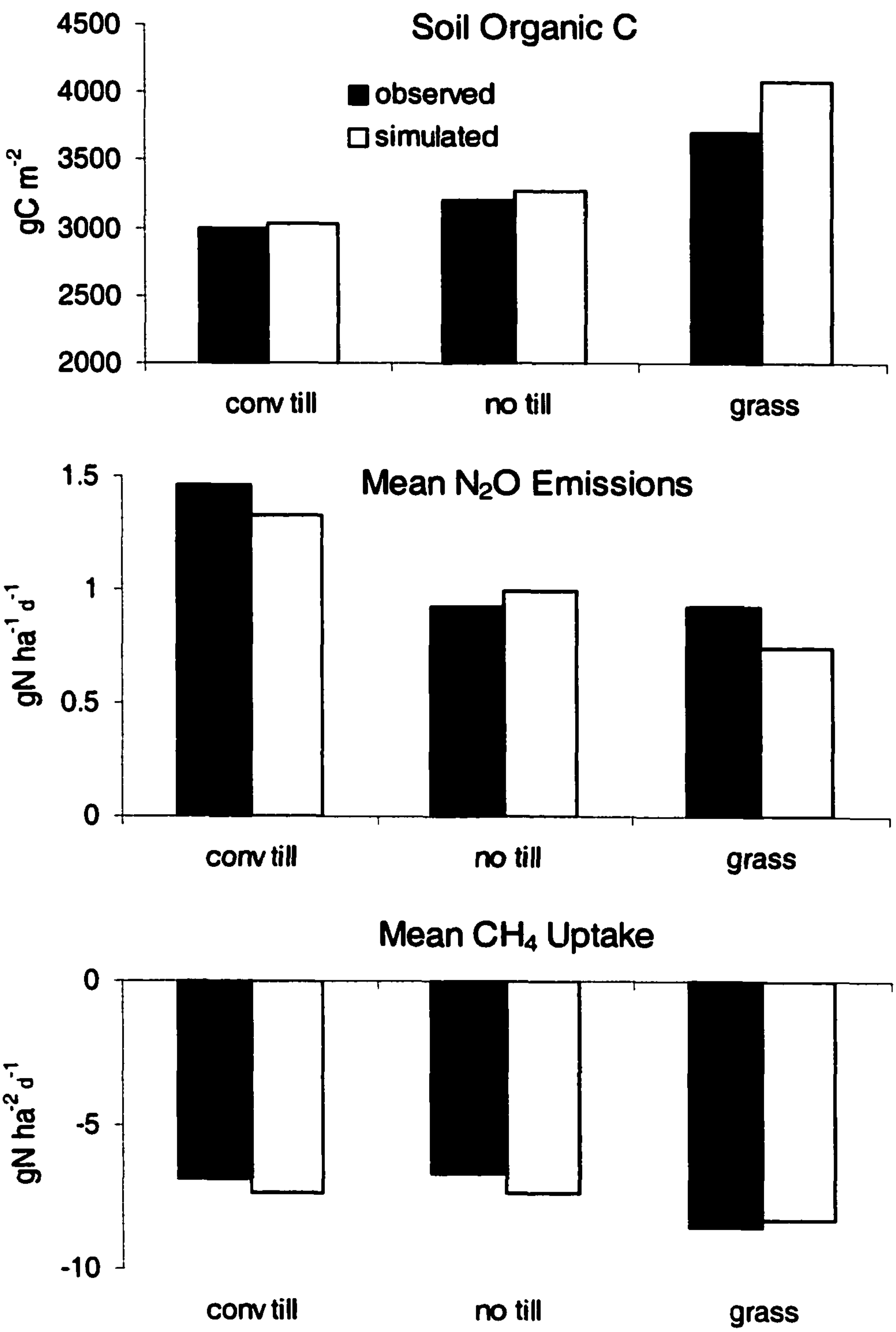
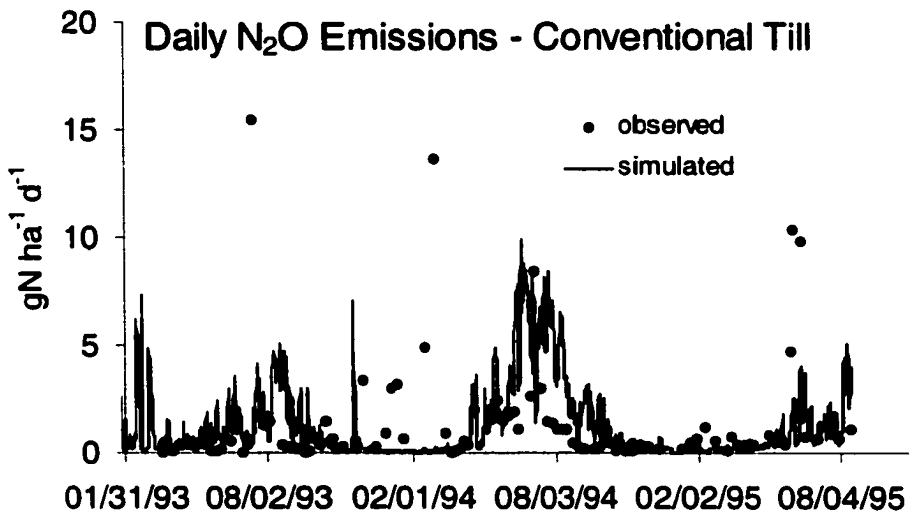
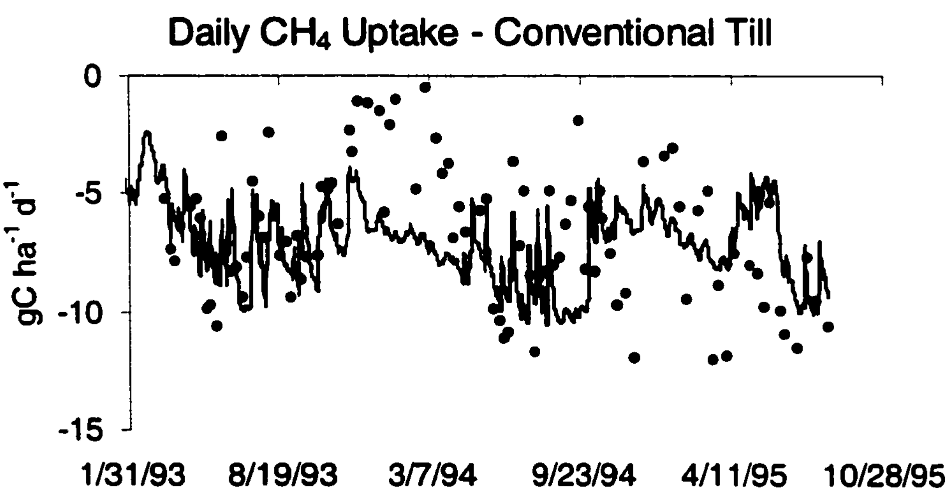

Soil Organic C
observed
simulated
$gC\ m^{-2}$
4500
4000
3500
3000
2500
2000
conv till
no till
grass
Mean N_2O Emissions
$gN\ ha^{-1}\ d^{-1}$
1.5
1
0.5
0
conv till
no till
grass
Mean CH_4 Uptake
$gN\ ha^{-2}\ d^{-1}$
0
-5
-10
conv till
no till
grass

Figure 6.1

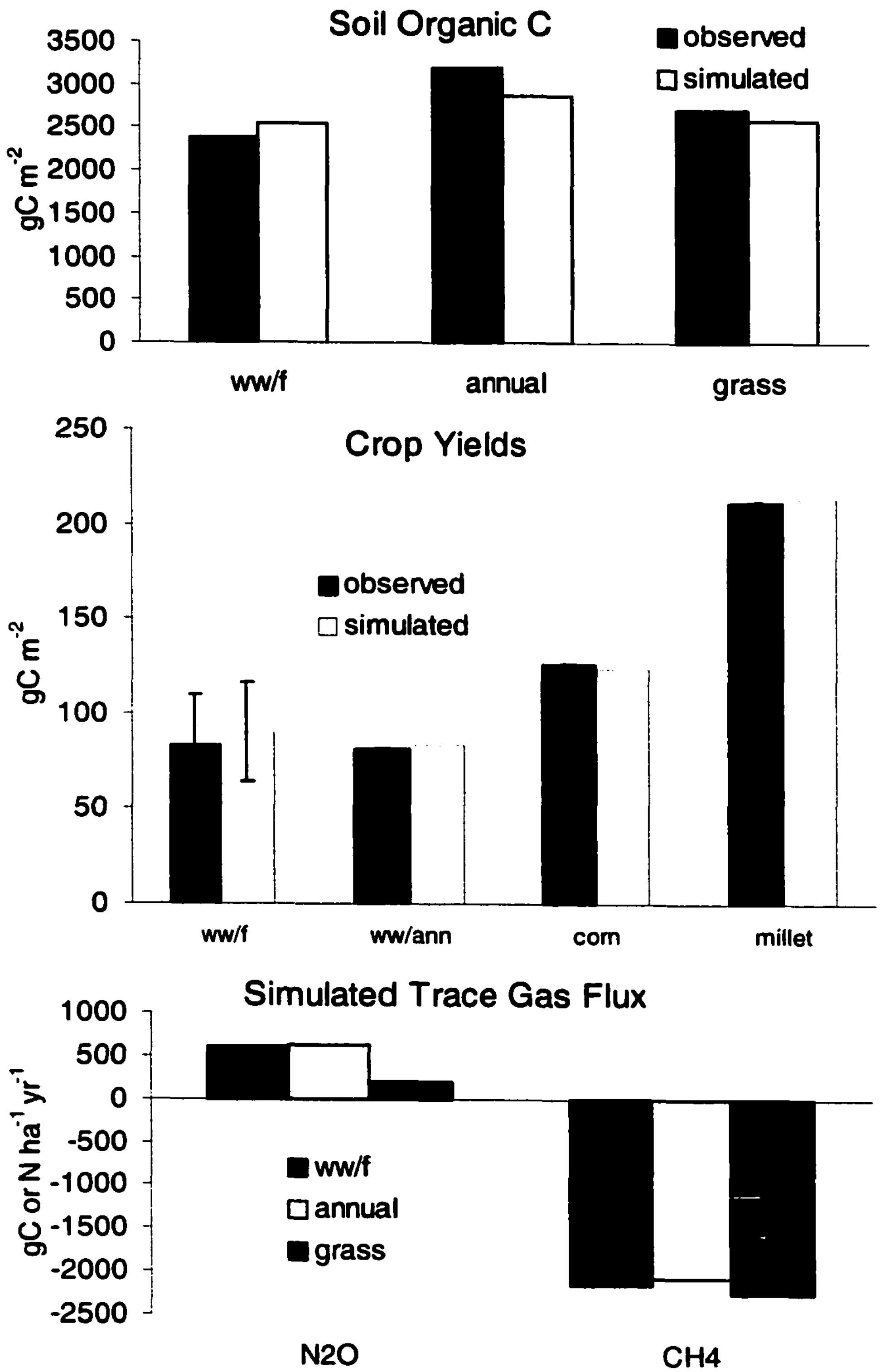


Daily N2O Emissions - Conventional Till
20
15
10
5
0
gN ha-1 d-1
observed
simulated
01/31/93 08/02/93 02/01/94 08/03/94 02/02/95 08/04/95



Daily CH4 Uptake - Conventional Till
0
-5
-10
-15
gC ha-1 d-1
1/31/93 8/19/93 3/7/94 9/23/94 4/11/95 10/28/95

Figure 6.2



Soil Organic C
observed
simulated
gC m-2
3500
3000
2500
2000
1500
1000
500
0
ww/f
annual
grass
Crop Yields
gC m-2
250
200
150
100
50
0
observed
simulated
ww/f
ww/ann
corn
millet
Simulated Trace Gas Flux
gC or N ha-1 yr-1
1000
500
0
-500
-1000
-1500
-2000
-2500
ww/f
annual
grass
N2O
CH4

Figure 6.3

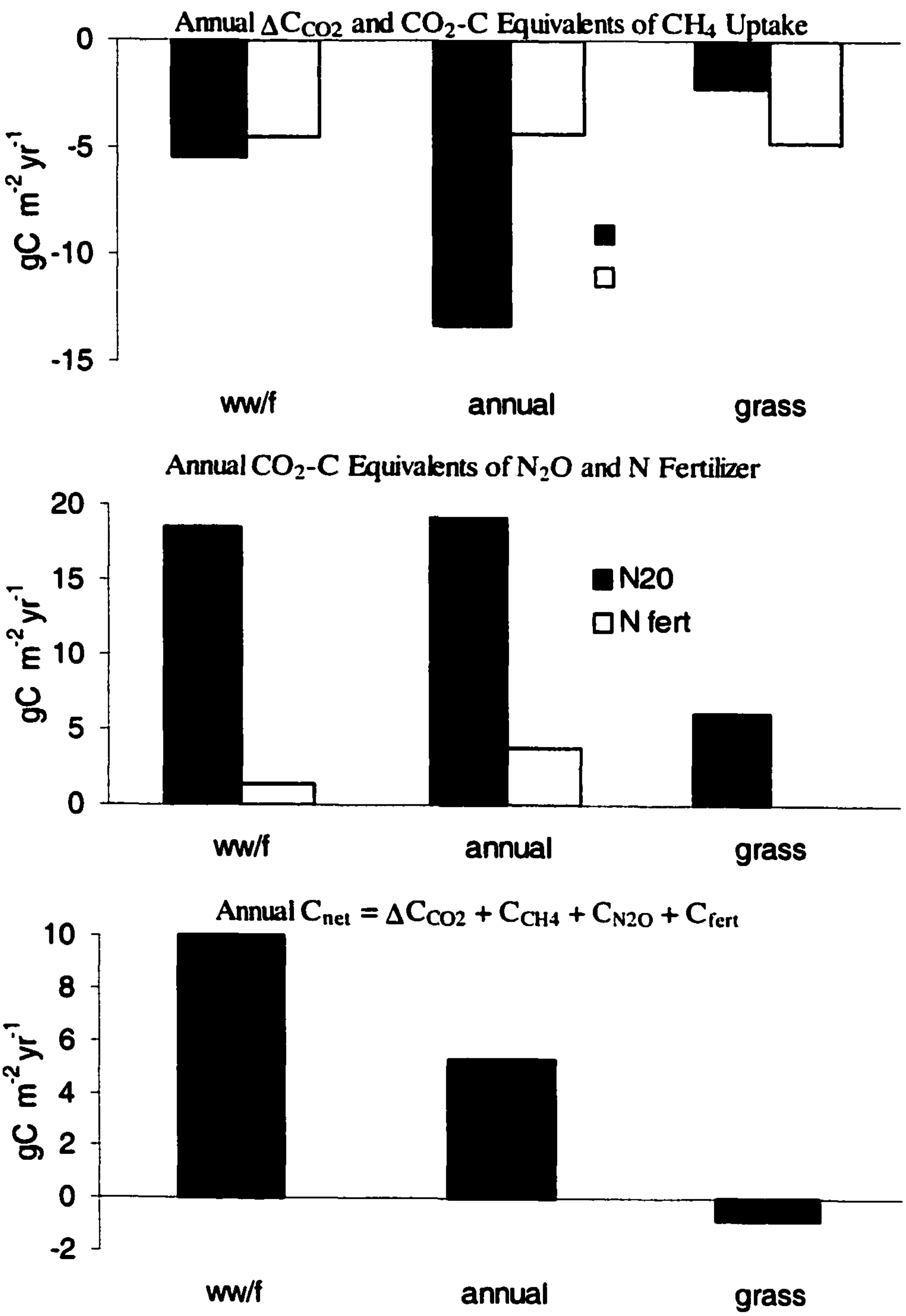

Annual ΔCCO2 and CO2-C Equivalents of CH4 Uptake
0
-5
-10
-15
gC m-2 yr-1
ww/f
annual
grass
Annual CO2-C Equivalents of N2O and N Fertilizer
20
15
10
5
0
gC m-2 yr-1
N20
N fert
ww/f
annual
grass
Annual Cnet = ΔCCO2 + CCH4 + CN2O + Cfert
10
8
6
4
2
0
-2
gC m-2 yr-1
ww/f
annual
grass

Figure 6.4

CHAPTER 7

REGIONAL ASSESSMENT OF NET GREENHOUSE GAS FLUXES FROM AGRICULTURAL SOILS IN THE USA GREAT PLAINS UNDER CURRENT AND IMPROVED MANAGEMENT

Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R., Peterson, G.A. 2002. Regional assessment of net greenhouse gas fuluxes from agricultural soils in the USA Great Plains under current and improved management. In: van Ham, J., Baede, A.P.M., Guicherit, R., Williams-Jacobs, J.G.F.M. (Eds.), *Proceedings of the Third International Symposium on Non-*CO_2 *Greenhouse Gases*, in press, p 469-474. Millpress, Rotterdam, the Netherlands.

Abstract

The DAYCENT ecosystem model was used to compare the effects of land management on net greenhouse gas fluxes (GHG_{net}) and crop yields for the dominant agricultural systems in the Great Plains. Improved land management included conversion to no-till cultivation and reduction of summer fallow periods by replacing winter wheat cropping with alternative rotations that are economically viable for different precipitation regimes within the Great Plains. N_2O emissions, CH_4 uptake, CO_2 fluxes, and the CO_2 costs of N fertilizer production were converted to a common unit of CO_2-C equivalents and summed to obtain GHG_{net}. Most of the agricultural soils in this region are moderate to strong GHG_{net} sources under current management. Simulations suggest that improved management can significantly decrease GHG_{net} while maintaining or increasing grain yields for the majority of the agricultural land in the Great Plains.

Introduction

Agricultural soils are an important source of greenhouse gas (GHG) emissions, responsible for ~20% of the global anthropogenic GHG effect (Lal et al. 1998). Most of the GHG effect from agriculture is from N_2O emissions associated with fertilizer application and CH_4 emissions from rice paddies due to decomposition of organic matter under anaerobic conditions. Cropped upland (non-flooded) soils are a minor sink of atmospheric CH_4. Agricultural soils can be a source or sink of CO_2 depending on crop type, fertilizer application rates, cultivation, and other factors that influence C inputs and decomposition rates. Cropped upland soils emit more N_2O (Mosier & Kroeze 2000) and absorb less CH_4 (Bronson & Mosier 1994) than native systems under similar environmental conditions. The DAYCENT ecosystem model was used to assess net GHG fluxes (GHG_{net}) and crop yields for agricultural soils in the central U.S. Great Plains region under current and improved land management. GHG_{net} was calculated by accounting for fluxes of CO_2, N_2O and CH_4, and the CO_2 costs of N fertilizer production.

Approximately 15 million of the 21 million ha used for agriculture in the Great Plains are cropped with winter wheat. Annual precipitation ranges from less than 35 cm in the western Great Plains to more than 100 cm in the eastern Great Plains. Winter wheat is the dominant crop in this region because precipitation is usually too low to support summer cropping without irrigation and water for irrigation is limited. Winter wheat/fallow rotations are used in the western portion of the Great Plains (eastern Colorado, southeast Wyoming, eastern Nebraska) where annual precipitation is less than 45-50 cm and droughts are common. In the majority of Kansas, precipitation is in the 50-75 cm range and annual winter wheat is the primary crop. Irrigated corn is the major crop in central Nebraska while precipitation is sufficient to support rain fed corn in eastern Nebraska.

Winter wheat, either sown annually or in wheat/fallow rotations, accounts for ~70% of the land used for agriculture in the Great Plains. Fields are kept fallow (vegetation free) by cultivation or herbicide application during the summer months before planting winter wheat in autumn. This system has been traditionally used in the Great Plains because water is stored in soil during the fallow months so that seedling establishment is virtually assured and risk of catastrophic crop failure is minimized. However, there is evidence that conversion to no till cultivation and reducing the summer fallow period leads to increased crop yields (Peterson et al. 2000) and higher long term economic returns for farmers (Dhuyvetter et al. 1996). We present model evidence to support data showing that improved management can lead to higher crop yields and increased soil organic carbon (Peterson et al. 1998). DAYCENT simulations also suggest that conversion to improved management can significantly reduce N_2O emissions associated with agriculture.

Materials and Methods

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. Soil texture data and land use history are required for each simulated site, and daily maximum/minimum temperature and precipitation data are used to drive the model. DAYCENT can simulate disturbance events and management practices such as fire, grazing, cultivation, and crop amendments. Major submodels simulate plant productivity, decomposition of dead plant material and soil organic matter (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, the C:N and lignin:N ratios of the pools, soil water/temperature factors, and soil physical properties related to texture. SOM is divided into three pools based on decomposition rates (Parton et al. 1994). Decomposition of SOM and external nutrient additions supply the mineral N pool which is available for plant growth and microbial processes that result in N transformations and trace gas fluxes. Plant growth is controlled by vegetation-specific maximum growth and temperature/water response parameters, 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, phenology, 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).

DAYCENT simulates N gas (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, and soil physical properties that influence gas diffusion rates (Del Grosso et al. 2000a). 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. CH_4 oxidation is controlled by soil gas diffusivity, water content, and temperature (Del Grosso et al. 2000b). CH_4 oxidation rates are assumed to be limited by gas diffusivity when soil water content is too high and by moisture stress on biological activity when water is too low. Clay soils are assumed to have a higher optimum water content for CH_4 oxidation than sandy soils.

Simulations and data analysis

VEMAP (Vegetation/Ecosystem Modeling & Analysis Project, Schimel et al. 2000) land use class, soil texture, and daily climate data resolved at the 0.5° latitude/longitude scale were used to drive the model. We simulated 100 years of historical land use followed by 50 years of the current management or 50 years of improved management. The historical portion of the simulations included the introduction of improved cultivars at appropriate times and historically accurate levels of fertilizer application. Improved management consisted of conversion to no till and reduction of the summer fallow period in cells where winter wheat is the dominant crop. This is possible because higher soil water contents associated with no-till cultivation compensate for the water storage benefits of the fallow period. We assumed that irrigation levels would not change because it is unlikely that more water will be made available for irrigation in the future. Conversion to no-till was the sole management change in areas currently cropped with rain-fed or irrigated corn. Table 7.1 summarizes current and improved management scenarios.

Output files for soil organic carbon (SOC), N_2O emissions, CH_4 uptake, and grain yields were compiled and used to calculate average yearly values for these variables for successive 12-year intervals. The change in SOC after 12 years of a particular management practice is assumed to represent net C exchange between the atmosphere and the soil because it integrates CO_2 fixation from photosynthesis and CO_2 losses from SOC decomposition. N_2O emissions and CH_4 uptake were converted to CO_2-C equivalents by accounting for molecular stoichiometry and assuming that N_2O and CH_4 have 311 and 25 times, respectively, the global warming potential of CO_2 on a per molecule basis. We also assumed that the production of each gram of N fertilizer results in the release of 0.8 g CO_2-C. GHG_{net} was calculated by summing the SOC and the CO_2-C equivalents of N_2O, CH_4, and N fertilizer production. GHG_{net} does not represent a full GHG accounting because the CO_2 costs of farm equipment operation, etc., were not included.

Results

Figure 7.1 shows comparisons of average annual GHG_{net} for the 1st 12-year period of conventional and improved management in the central Great Plains. Simulations show that most of this land is a GHG_{net} source under current management. The cells that are large GHG emitters in Kansas are cropped with annual winter wheat and the more moderate emitters in Colorado, Wyoming, and western Nebraska are cropped with winter wheat/fallow. The cells in Colorado, Nebraska, and Kansas that are GHG_{net} sinks under current management are cropped with rain-fed or irrigated corn. Conversion to improved management led to lower total GHG emissions than current management in all cases. GHG_{net} decreased to a large extent in the areas converted from annual winter wheat to winter wheat/corn soy and to a moderate extent in areas converted from winter wheat/fallow to winter wheat/fallow/corn. Conversion from conventional till annual corn and winter wheat/corn rotations to no-till cropping with the same rotations showed moderate to minor reductions in GHG_{net}.

Figure 7.2 shows how GHG_{net} changes during consecutive 12-year periods for a typical cell in Kansas where the conventional management is annual winter wheat and improved management is winter wheat/soy/corn rotations. Under conventional management, this soil is always a GHG_{net} source. SOC is close to equilibrium under current management and climate-driven variability in N_2O fluxes is largely responsible for the variation in GHG_{net}. In contrast, changes in GHG_{net} are driven primarily by changes in SOC under improved management. During the 1^{st} 12-year period, CO_2 is sequestered and the soil is a strong GHG_{net} sink under improved management. Sink strength diminishes as SOC approaches saturation and the soil becomes a GHG_{net} source during the 4^{th} 12-year interval. Although the GHG_{net} sink under improved management is temporary, GHG_{net} is significantly higher under conventional compared to improved management during all time periods simulated. N_2O emissions were approximately two times lower under improved management because the soil sequesters organic matter so more N is immobilized and unavailable for processes that result in N gas losses. CH_4 uptake was ~10% lower under improved management. No-till cultivation leads to higher soil water content and cooler soil temperatures which tend to decrease CH_4 oxidation rates. The increases in SOC and reductions in N gas losses far outweigh the small decrease in CH_4 uptake associated with improved management.

Simulated average crop yields were higher under improved management in all cases (Fig. 7.3). Conversion from conventional till winter wheat/fallow to no-till winter wheat/fallow/corn showed a moderate increase in yields while the increases for the other cropping systems were minor. Corn had the highest yields because corn is a fast growing crop and is irrigated or grown in areas of relatively high precipitation. When calculating average annual grain yields for the wheat/fallow and wheat/fallow/corn rotations zero grain yields during the fallow years were included.

Discussion

Under conventional management, most of the agricultural soils in the U.S. Great plains are GHG_{net} sources. Winter wheat is the most common crop in this region and these soils are strong GHG_{net} sources because N_2O emissions are high and SOC is depleted. During the summer fallow period the land is kept vegetation free by plowing or herbicide application. Consequently, loss of C from decomposition exceeds C inputs, so SOC decreases and the system is a net CO_2 source. N_2O emissions are often substantial during the summer fallow period because plants are not present to compete for mineralized N from decomposition and microbial processes that result in N_2O emissions (nitrification and denitrification) are enhanced. Under current management, areas cropped with irrigated or rain-fed corn are net CO_2 sinks. The reason for this is that before conversion to corn, these areas were depleted of SOC due to many years of wheat/fallow cropping. Upon conversion to irrigated summer corn annual NPP exceeded decomposition and C was sequestered in the soil.

DAYCENT model results suggest that improved management can mitigate GHG emissions while maintaining or increasing regional crop yields. Areas that have traditionally been used for winter wheat cropping have the most potential to reduce GHG_{net} upon conversion to improved management because these soils are depleted in SOC and are substantial N_2O emitters. Conversion to no till conserves soil water and can allow for successful summer cropping without irrigation. Conversion to winter wheat/corn/soy in Kansas showed larger GHG_{net} reductions than conversion to winter wheat/fallow/corn in the western portion of the region. This is a function of higher rainfall in Kansas supporting a higher proportion of cropped summers (2/3) than the winter wheat/fallow/corn (1/3) rotation used in the drier areas. Regions that are currently cropped with corn have minimal potential to decrease GHG_{net} upon conversion to improved management because the option of decreasing summer fallow is not available. Conversion to no till should lead to increased C sequestration in these soils, but the model predicts that grain yields will also decrease. This is consistent with data showing that conversion to no till temporarily decreases yields but this effect diminishes as SOC increases and soil quality improves.

Model results showing increased SOC under improved management are consistent with data from eastern Colorado (Peterson et al. 1998) and western Nebraska (Kessavalou et al. 1998). Improved management effects both C input and C output rates. Reduction of the summer fallow period results in increased C inputs to the system and no till cultivation reduces C losses from decomposition. Lower simulated N_2O emissions under improved management largely result from reduction of the summer fallow period. When crops are grown during the summer, plants compete for mineral N so N gas losses are reduced. Appropriate N_2O gas flux data are needed to verify this model prediction.

Conversion to no-till and reduction of the summer fallow period will lead to higher long-term yields, but there are some disadvantages to this change of management. Summer cropping has higher costs than winter wheat, although yields and long term profits are higher (Dhuyvetter et al. 1996). Occasionally, summer drought will lead to crop failure and short-term losses for the farmer. We caution that the simulated benefits of improved management may be exaggerated because the model is not sensitive to spring freezing and hail events that can entirely destroy real-world crops. Also, there are start-up costs associated with any changes in land management. Nevertheless, these simulations provide evidence that improved land management can significantly reduce GHG_{net} from agricultural soils while maintaining or enhancing long term economic yields.

References

Bronson, K.F. & Mosier, A.R. 1994. Suppression of methane oxidation in aerobic soil by nitrogen fertilizers, nitrification inhibitors, and urease inhibitors. *Biol. Ferilt. Soils, 17*: 263-268.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Kulmala, A.E. & Phongpan, S. 2000a. General model for N_2O and N_2 gas emissions from soils due to denitrification. *Global Biogeochemical Cycles 14*: 1045-1060.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Potter,C.S., Borken, W., Brumme, R., Butterbach-Bahl, K., Crill, P.M., Dobbie, K. & Smith, K.A. 2000b.

General CH_4 oxidation model and comparisons of CH_4 oxidation in natural and managed systems. *Global Biogeochemical Cycles 14*: 999-1019.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S. & Schimel, D.S. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In M. Schaffer, L. Ma, & S. Hansen (eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*: 303-332. Boca Raton, Florida: CRC Press.

Dhuyvetter, C.R., Thompson, R.C., Norwood, C.A. & Halvorson, A.D. 1996. Economics of dryland cropping systems in the Great Plains: A review. *J. Prod. Ag. 9*: 216-222.

Eitzinger, J., Parton, W.J. & Hartman, M.D. 2000. Improvement and validation of a daily soil temperature submodel for freezing/thawing periods. *Soil Science 165*: 525-534.

Kelly, R.H., Parton, W.J., Hartman, M.D., Stretch, L.K., Ojima D.S. & Schimel, D.S. 2000. Intra and interannual variability of ecosystem processes in shortgrass steppe. *Journal of Geophysical Research: Atmospheres 10:* 20,093-20,100.

Kessavalou, A., Mosier, A.R., Doran, J.W., Drijber, R.A., Lyon, D.L. & Heinemeyer, O. 1998. Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. *Journal of Environmental Quality 27*: 1094-1104.

Lal, R., Kimble, J.M., Follett, R.F. & Cole, C.V. 1998, *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Ann Arbor Press.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton, W.J. 1993, *CENTURY soil organic matter model environment, Technical documentation, Agroecosystem version 4.0.* Fort Collins, CO: Colorado State University.

Mosier, A.R. & Kroeze, C. 2000. Potential impact on the global atmospheric N_2O budget of the increased nitrogen input required to meet future global food demands. *Chemosphere-Global Change Science 2*: 465-473.

Parton, W.J., Ojima, D.S., Cole C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In, *Quantitative Modeling of Soil Forming Processes*: 147-167. Madison, WI: Soil Science Society of America.

Parton, W.J., Hartman, M.D., Ojima, D.S. & Schimel, D.S. 1998. DAYCENT: Its land surface submodel: description and testing. *Global Planetary Change 19*: 35-48.

Parton, W.J., Holland, E.A., Del Grosso, S.J., Hartman, M.D., Martin, R.E., Mosier, A.R., Ojima, D.S. & Schimel, D.S. Generalized model for NO_x and N_2O emissions from soils. *Journal of Geophysical Research: Atmospheres*, in press.

Peterson, G.A., Halvorson, A.D., Havlin, J.L., Jones, O.R., Lyon, D.L. & Tanaka, D.L. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. *Soil Tillage and Research 47*: 207-218.

Peterson, G.A., Westfall, D.D., Peairs, F.B., Sherrod, L., Poss, D., Gangloff, W., Larson, K., Thompson, D.L., Ahuja, L.R., Koch, M.D. & Walker, C.B. 2000. *Sustainable dryland agroecosystem management, TB00-03*. Fort Collins, CO: Colorado State University.

Schimel, D., Melillo, J., Tian, H., McGuire, A.D., Kicklighter, D., Kittel, T., Rosenbloom, N., Running, S., Thornton, P., Ojima, D., Parton, W., Kelly, R., Sykes, M., Neilson, R. & Rizzo B. 2000. Contribution of increasing CO_2 and climate to carbon storage by ecosystems of the United States. *Science 287*: 2004-2006.

Tables

Table 7.1. Land management scenarios for the central USA Great Plains simulated by DAYCENT.

Conventional Management			Improved Management		
Crop Rotation	Fertilizer kgN ha^{-1} yr^{-1}	Tillage	Crop Rotation	Fertilizer KgN ha^{-1} yr^{-1}	Tillage
wheat/fallow	38.5	conventional	wheat/fallow/corn	55	no-till
corn	100	conventional	corn	100	no-till
wheat/corn	90	conventional	wheat/corn	90	no-till
annual wheat	80	conventional	wheat/soy/corn	63	no-till

List of Figures

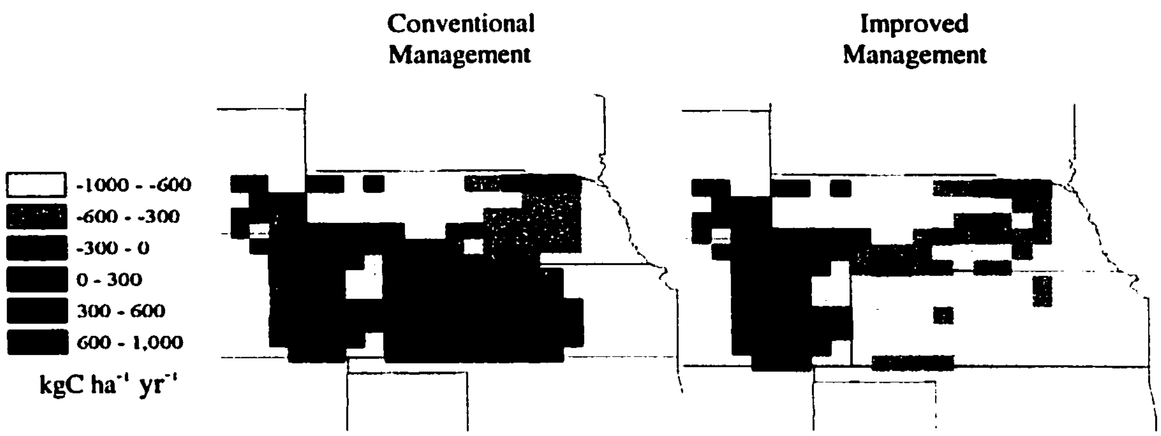


Figure 7.1

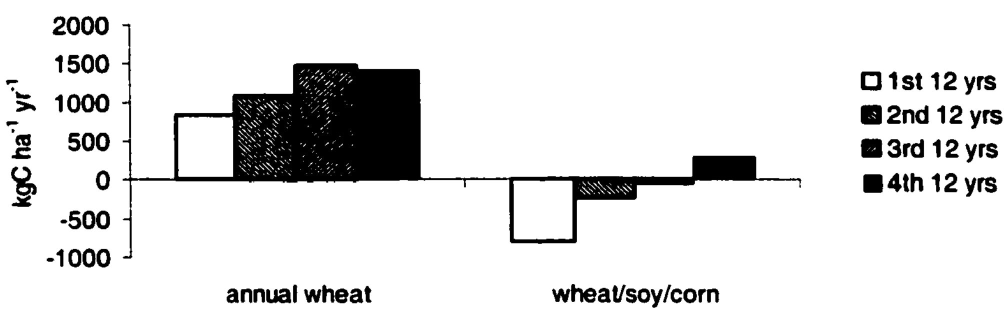


Figure 7.2

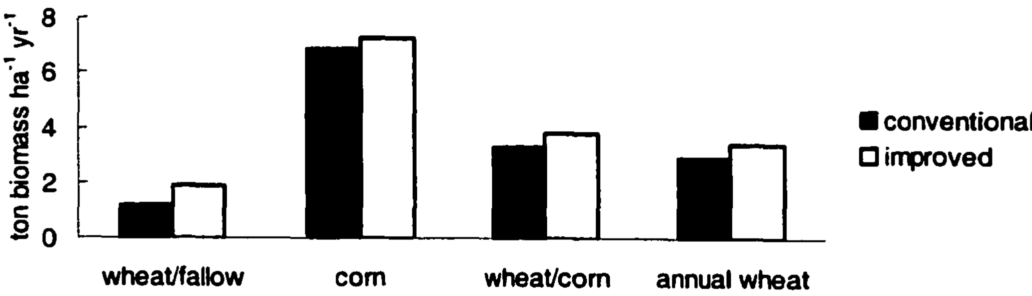

ton biomass ha^{-1} yr^{-1}
8
6
4
2
0
wheat/fallow
corn
wheat/corn
annual wheat
conventional
improved

Figure 7.3

CHAPTER 8

SIMULATED EFFECTS OF TILLAGE AND TIMING OF N FERTILIZER APPLICATION ON NET GREENHOUSE GAS FLUXES AND N LOSSES FOR AGRICULTURAL SOILS IN THE MIDWESTERN USA

Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R. 2002. Simulated effects of tillage and timing of N fertilizer application on net greenhouse gas fluxes and N losses for agricultural soils in the Midwestern USA. In: van Ham, J. et al. (Eds.), *Proceedings of the Third International Symposium on Non-CO_2 Greenhouse Gases*, p. 23-28. Millpress, Rotterdam, the Netherlands.

Abstract

The DAYCENT ecosystem model was used to simulate net greenhouse gas emissions (GHG_{net}), N gas losses, and N leaching for corn and corn/soybean rotations in the Midwestern USA. The effects of tillage and timing of fertilizer application on GHG_{net} and N losses were calculated for clay loam and sandy loam soils. N_2O emissions, CH_4 uptake, changes in soil organic carbon (SOC), and the CO_2 costs of N fertilizer production were converted to a common unit of CO_2-C equivalents and summed to obtain GHG_{net}. GHG_{net} and grain yields were higher for the finer textured soil while total N gas losses and leached N were higher for the coarser soil. Conversion to no-till increased soil organic carbon substantially, but also led to slightly lower crop yields and higher N leaching. Split application of fertilizer increased crop yields and SOC and decreased N losses from leaching and N gas fluxes.

Introduction

Agricultural soils are responsible for the majority of anthropogenic N_2O emissions (Mosier & Kroeze 2000) and a large portion of anthropogenic CH_4 emissions (Lal et al. 1998). Although emissions of these gases are much lower than that of CO_2, CH_4 and N_2O account for ~20% of the anthropogenic greenhouse effect because these gases have a much stronger global warming potential (GWP) than CO_2 on a per molecule basis (Lal et al. 1998). Consequently, reduction of CH_4 and N_2O emissions from agricultural soils has the potential to significantly mitigate the anthropogenic greenhouse effect. Agricultural soils are often net sources of CO_2, but conversion to no-till cultivation can lead to sequestration of CO_2-C in soil organic carbon (SOC, Nyborg et al. 1995). A substantial amount of N from agricultural soils is leached into grounder water and streams but optimization of the timing and amount of fertilizer applied has the potential to decrease N losses from leaching and N gas emissions. The DAYCENT ecosystem model was used to assess the effects of tillage and timing of N fertilizer application on net greenhouse gas emissions (GHG_{net}), N gas losses, N leaching, and grain yields for the dominant crops in the Midwestern USA. GHG_{net} was calculated by accounting for changes in SOC, the CO_2 equivalents of N_2O and CH_4 fluxes, and the CO_2 costs of N fertilizer production.

Materials and Methods

DAYCENT model description

DAYCENT (Parton et al. 1998, Kelly et al. 2000, Del Grosso et al. 2001) is a terrestrial ecosystem model used to simulate C and N flows through the atmosphere, soils, and vegetation. Daily maximum/minimum temperature and precipitation data are used to drive the model. Site specific soil texture data and land use history are also required. Disturbance events and management practices such as fire, grazing, cultivation, and crop amendments can be scheduled and alternative land uses can be compared. Major submodels simulate plant productivity, decomposition of dead plant material and SOC, soil water and temperature dynamics, and trace gas (CH_4, N_2O, NO_x) fluxes. Flows of C and nutrients are controlled by the amount of C in the various pools, the C:N and lignin:N ratios of the pools, soil water/temperature factors, and soil physical properties related to texture. Soil organic matter (SOM) is divided into three pools based on decomposition rates (Parton et al. 1994). Decomposition of SOM and external nutrient additions supply the mineral N pool that is available for plant growth and microbial processes that result in N transformations and trace gas fluxes. Plant growth is controlled by vegetation-specific maximum growth and temperature/water response parameters, 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, phenology, 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). Leaching is a function of NO_3^- concentration, soil texture, and water flow down the soil profile.

DAYCENT simulates N gas (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, and soil physical properties that influence gas diffusion rates (Del Grosso et al. 2000a). 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 (Martin et al. 1998). CH_4 oxidation is controlled by soil gas diffusivity, water content, and temperature (Del Grosso et al. 2000b). CH_4 oxidation rates are assumed to be limited by gas diffusivity when soil water content is too high and by moisture stress on biological activity when soil water content is too low.

Simulations and data analysis

We simulated 100 years of traditional agriculture (initialization) followed by 30 years of contrasting treatments. A 100 year daily weather file from Lafayette, Indiana (MAT = 10.2 , MAP = 94 cm) was used to drive simulations of sandy loam and clay loam soils. The initialization portion of the simulations included historical cropping rotations, improvement of crop varieties, traditional tillage practices, and N fertilizer applications beginning in 1950 that were gradually increased to modern levels. Treatments consisted of varying soil tillage and timing of fertilizer applications (Table 8.1) for annual corn and corn/soybean rotations. During the years when corn was planted, fertilizer was applied all in a single application or in two applications (split N application) of 50% each.

Output files for SOC, N gas (N_2O, NO_x, N_2) emissions, N leached, CH_4 uptake, plant N uptake, and grain yields were compiled and used to calculate average yearly values for these parameters. The change in SOC after 30 years of a particular management practice is assumed to represent net C exchange between the atmosphere and the soil because it integrates CO_2 fixation from photosynthesis and CO_2 losses from SOC decomposition. N_2O emissions and CH_4 uptake were converted to CO_2-C equivalents by using molecular stoichiometry and assuming that N_2O and CH_4 have 311 and 25 times, respectively, the global warming potential of CO_2 on a per molecule basis. We also assumed that the production of each gram of N fertilizer resulted in the release of 0.8 g CO_2-C. GHG_{net} was calculated by summing the SOC and the CO_2-C equivalents of N_2O, CH_4, and N fertilizer production. GHG_{net} does not represent a full GHG accounting because the CO_2 costs of farm equipment operation, transportation of products, and other factors were not included. Emissions of NO_x, N_2O, and N_2 were summed to obtain total N gas losses.

Results

Figure 8.1 shows average annual SOC, CO_2-C equivalents of N_2O and CH_4, and GHG_{net} for 30-year simulations of corn cropping in clay loam and sandy loam soils. Split fertilizer application led to slightly higher rates of SOC sequestration but conversion to no-till cultivation yielded substantial gains in SOC for both soil types. Split fertilizer application and conversion to no-till resulted in minor reductions of N_2O emissions but had no affect on CH_4 uptake. The sandy loam emitted slightly less N_2O than the clay loam. Under conventional tillage, both sandy loam and clay loam soils were strong GHG_{net} sources while conversion to no-till greatly reduced GHG_{net}. Split fertilizer application led to a minor reduction in GHG_{net}. Simulations of corn/soybean rotations showed the same patterns as corn and values for GHG_{net} were similar. The major differences with corn/soybean cropping were lower rates of SOC sequestration and lower N_2O emissions.

Soil texture has a stronger effect on plant N uptake (higher in the clay loam) than the management options that were simulated (Fig. 8.2). Split N application led to a minor increase in plant N uptake while no-till cultivation had the opposite effect. Total N gas losses were higher from sandy loam and conversion to no-till decreased N gas losses, especially for the sandy loam. Split N application led to minor reductions in N gas losses. N leaching was higher from the sandy loam than the clay loam. Split N application decreased leaching substantially but no-till increased leaching. Treatment effects were similar for simulations of corn/soybean rotations. Magnitudes of plant N uptake were higher for corn/soybean cropping and N gas losses and N leaching were lower.

Discussion

DAYCENT simulations show that land management interacts with soil texture and climate to control GHG fluxes, N losses, and grain yields. Conversion to no-till cultivation led to significant increases in SOC and reduced GHG_{net} to roughly neutral levels. However, conversion to no-till also resulted in higher N leaching and lower grain yields. This is consistent with data showing decreased yields under no-till cultivation for some cropped soils in Ohio (Dick et al. 1991). The decrease in grain yields associated with no-till is related to decreased N mineralization and a shorter growing season resulting from lower soil temperatures. Higher leaching results from higher soil water levels associated with no-till. These undesirable effects may be compensated by increased soil nutrient holding capacity that should occur after no-till has been practiced for a sufficient time period. CH_4 uptake did not vary among treatments because DAYCENT does not simulate changes in soil physical dynamics that drive CH_4 uptake rates. Split fertilizer application had a stronger effect on N leaching than on N gas emissions. N gas emissions are driven to a large extent by N cycling while N leaching is largely driven by N excess. Split N fertilizer application is expected to more strongly affect N excess than N cycling.

Soil texture is an important control on N dynamics. The clay loam had higher plant N uptake (and grain yields), lower N gas losses, and lower N leaching. Finer textured soils have higher water and nutrient holding capacities which enhance plant growth and diminish leaching. Lower redox potentials associated with clay soils result in lower NO_x emissions and higher N_2O emissions. Because NO_x emissions are approximately an order of magnitude higher than N_2O and N_2 emissions in these soils, the clay loam had lower total N gas losses. As soil texture becomes finer, N losses from the system decrease and N uptake by plants and grain yields tend to increase.

Simulations suggest that conversion to no-till can mitigate GHG_{net} for agricultural soils in the Midwestern USA. Split fertilizer application can lead to modest decreases in GHG_{net} and significant decreases in N leaching. The land management practices we simulated had similar effects on annual corn and corn/soybean rotations but N gas and N leaching losses were lower from the corn/soybean rotations. The costs and benefits of different management practices in terms of crop yields, GHG fluxes, and NO_3 leaching must be considered to develop optimal land management strategies for different soils.

References

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Kulmala, A.E. & Phongpan, S. 2000a. General model for N_2O and N_2 gas emissions from soils due to denitrification. *Global Biogeochemical Cycles 14*: 1045-1060.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Potter,C.S., Borken, W., Brumme, R., Butterbach-Bahl, K., Crill, P.M., Dobbie, K. & Smith, K.A. 2000b. General CH_4 oxidation model and comparisons of CH_4 oxidation in natural and managed systems. *Global Biogeochemical Cycles 14*: 999-1019.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S. & Schimel, D.S. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In M. Schaffer, L. Ma, & S. Hansen (eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*: 303-332. Boca Raton, Florida: CRC Press.

Dick, W.A., McCoy, E.L., Edwards, W.M. & Lal. R. 1991. Continuous application of no-tillage to Ohio soils. *Agron. J. 83*: 65-73.

Eitzinger, J., Parton, W.J. & Hartman, M.D. 2000. Improvement and validation of a daily soil temperature submodel for freezing/thawing periods. *Soil Science 165*: 525-534.

Kelly, R.H., Parton, W.J., Hartman, M.D., Stretch, L.K., Ojima D.S. & Schimel, D.S. 2000. Intra and interannual variability of ecosystem processes in shortgrass steppe. *Journal of Geophysical Research: Atmospheres 10:*, 20,093-20,100.

Lal, R., Kimble, J.M., Follett, R.F. & Cole, C.V. 1998, *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Ann Arbor Press.

Martin, R.E., Scholes, M.C., Mosier, A.R., Ojima, D.S., Holland, E.A. & Parton, W.J. 1998. Controls on annual emissions of nitric oxide from soils of the Colorado shortgrass steppe. *Global Biogeochem. Cycles, 12*: 81-91.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton, W.J. 1993, *CENTURY soil organic matter model environment, Technical documentation, Agroecosystem version 4.0.* Fort Collins, CO: Colorado State University.

Mosier, A.R. & Kroeze, C. 2000. Potential impact on the global atmospheric N_2O budget of the increased nitrogen input required to meet future global food demands. *Chemosphere-Global Change Science 2*: 465-473.

Nyborg, M., Solberg, E.D., Malhi, S.S. & Izaurralde, R.C. 1995. Fertilizer N, crop residue, and tillage alter soil C and N content in a decade. In R. Lal, J. Kimble, E. Levine & B.A. Stewart (eds.), *Soil Management and Greenhouse Effect*: 93-99. Boca Raton, Florida: CRC Press.

Parton, W.J., Ojima, D.S., Cole C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In *Quantitative Modeling of Soil Forming Processes*: 147-167. Madison, WI: Soil Science Society of America.

Parton, W.J., Hartman, M.D., Ojima, D.S. & Schimel, D.S. 1998. DAYCENT: Its land surface submodel: description and testing. *Global Planetary Change 19*: 35-48.

Parton, W.J., Holland, E.A., Del Grosso, S.J., Hartman, M.D., Martin, R.E., Mosier, A.R., Ojima, D.S. & Schimel, D.S. Generalized model for NO_x and N_2O emissions from soils. *Journal of Geophysical Research: Atmospheres*, in press.

Yienger, J.J. & Levy H. II. 1995. Empirical model of global soil biogenic NO_x emissions. *J. Geophys. Res. 100*: 11,447-11,464.

Tables

Table 8.1. Land management alternatives for annual corn and corn/soybean rotations in the Midwestern USA simulated by DAYCENT.

Simulation	Fertilizer (gN m^{-2})	Tillage
CT-1X15	May: 15	Conventional
CT-2X7.5	May: 7.5 June: 7.5	Conventional
NT-1X15	May: 15	No-Till
NT-2X7.5	May: 7.5 June: 7.5	No-Till

List of Figures

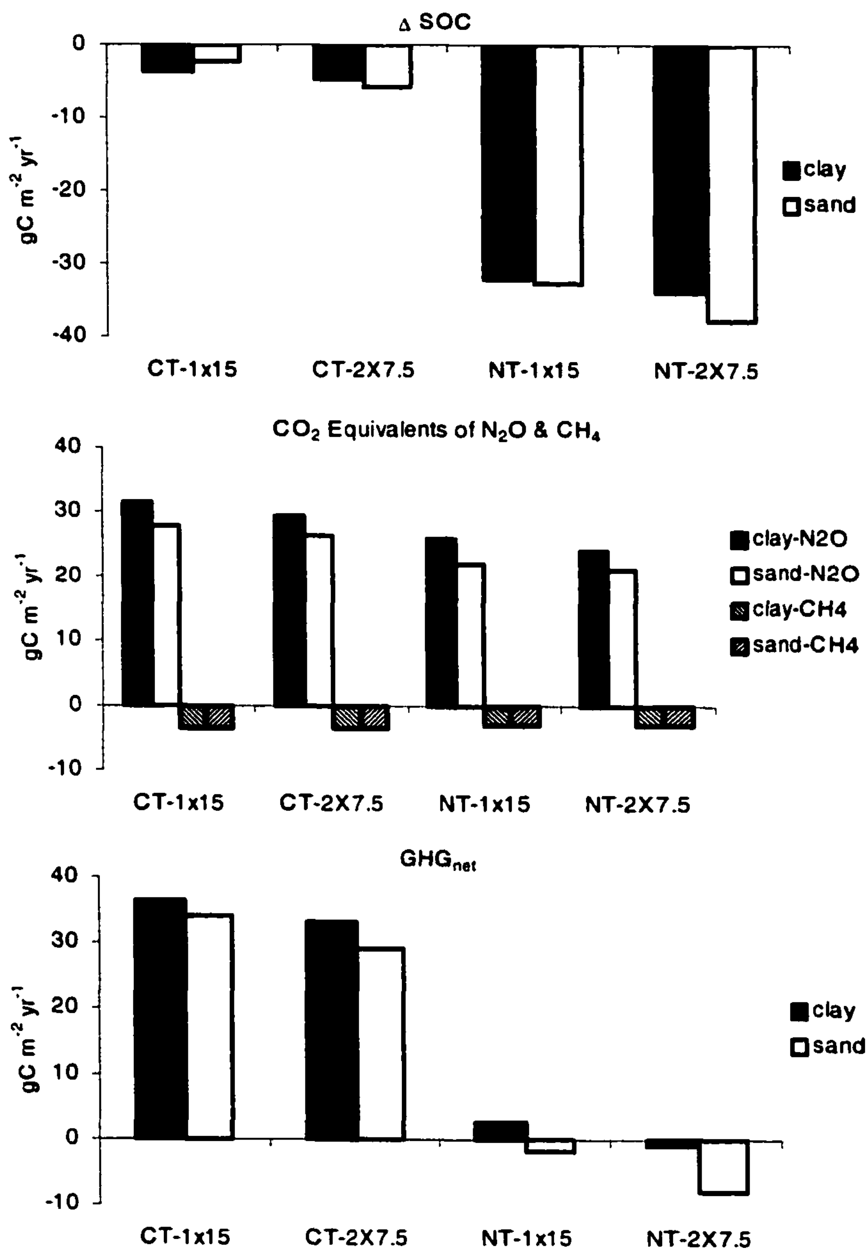

Δ SOC
0
-10
-20
-30
-40
gC m-2 yr-1
clay
sand
CT-1x15
CT-2X7.5
NT-1x15
NT-2X7.5
CO2 Equivalents of N2O & CH4
40
30
20
10
0
-10
clay-N2O
sand-N2O
clay-CH4
sand-CH4
GHGnet
clay
sand

Figure 8.1

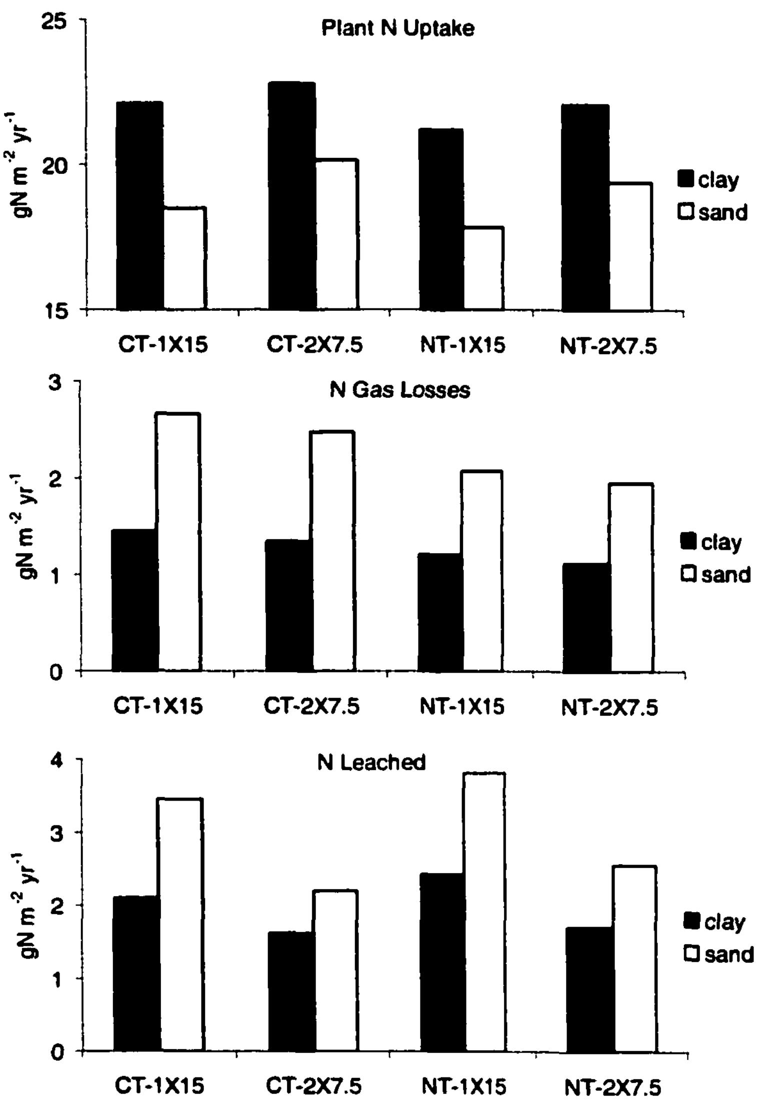

Plant N Uptake
gN m-2 yr-1
25
20
15
clay
sand
CT-1X15
CT-2X7.5
NT-1X15
NT-2X7.5
N Gas Losses
3
2
1
0
N Leached
4

Figure 8.2

CHAPTER 9

SUMMARY

This dissertation describes research conducted to improve, test, and apply the DAYCENT ecosystem model. Major model improvements include developing a soil organic matter (SOM) decomposition model, refinement of the plant growth subroutines, and new features designed to make the model more versatile. DAYCENT was tested using time series and site average values for important ecosystem variables from various data sets. The model was applied to calculate crop yields, nitrogen (N) losses, and net greenhouse gas fluxes for different land use scenarios.

One major objective of this research was to identify and quantify primary drivers of carbon (C) and N flows. Chapter 2 describes the development and testing of the submodel used to represent soil temperature and water limitation on decomposition. Data from the shortgrass steppe showed that temperature is a major control and soil water content a minor control on SOM decomposition rates. The equation used to represent the affect of soil temperature predicts that the Q_{10} increases as temperature decreases. That is, decomposition always varies directly with temperature but the response is more sensitive at lower temperatures. The equation was tested using independent soil carbon dioxide (CO_2) flux and temperature data from a variety of ecosystems. The r^2 value ranged from 16% to 85% across these sites, indicating that temperature is a primary control on decomposition rates in some, but not all soils. The decomposition subroutine predicts that soil water content has a minor effect on decomposition. This was supported for the vast majority of the soils tested. To some extent, the data support the hypothesis that CO_2 emissions from SOM decomposition can be simulated using soil temperature and water content (r^2 values for simulated versus observed CO_2 emissions were > 45 % more than half the time).

DAYCENT predicts that changes in vegetation cover or land management will alter soil organic carbon (SOC) levels. Measurements of SOC in Sidney, NE were highest in undisturbed grassland, intermediate in no till dryland agriculture, and lowest in conventional till dryland agriculture (Chapter 6). No till corn/soy/wheat rotations at Kellogg Biological Station (KBS) also had higher SOC compared to conventional till (Chapter 3). These observations support the hypothesis that conventional till cultivation decreases SOC. Data from Sterling, CO showed higher SOC in annual dryland cropping compared to winter wheat/fallow cropping (Chapter 6). This supports the hypotheses that dryland agriculture which involves a fallow season every other year mines soil of C and reduction of the fallow period will increase soil C.

DAYCENT predicts that N losses from gaseous emissions and leaching are sensitive to climate, vegetation cover, and land management. As N cycling and N availability increase, N losses should also increase. This is supported by data from various ecosystems showing that intensive agriculture has higher N_2O emissions than dryland agriculture and deciduous forests have higher emissions than grasslands (Figure 3.4). N cycling increases as precipitation increases and deciduous systems are wetter than grassland systems. The model also predicts that N_2O emissions should be lower under no till compared to conventional till cropping because no till leads to higher SOM levels which should tie up more N and leave less N available for the microbial processes that result in N_2O emissions. This was supported at the Sidney, NE dryland agriculture site (Chapter 6) but not at the KBS intensive agriculture site (Chapter 3). DAYCENT predicts that N leaching is higher in no till than conventional till cultivation (Chapter 8). The model also predicts that N leaching will be lower from finer textured than coarser textured soils and that leaching will be lower if fertilizer is applied in multiple applications instead of single application (Chapter 8). None of the hypotheses involving N leaching have yet been tested using observed data. The model predicts that CH_4 uptake is largely driven by soil gas diffusivity and it should be lower in cropped soils than in similar undisturbed soils. These hypotheses were supported in the soils tested but some agricultural soils showed somewhat higher or lower CH_4 uptake rates than predicted by the model (Chapter 3).

Another major objective of this research was to assess net greenhouse gas fluxes (GHG_{net}) from different systems and to identify land use practices that will decrease GHG_{net}. Sequestration of atmospheric CO_2 in SOC has been suggested as a means to compensate for anthropogenic GHG emissions. However, GHG levels are by definition a global problem and it is not reasonable to consider the effects of land use changes on CO_2 fluxes independent of non-CO_2 GHG fluxes. CH_4 and N_2O are important greenhouse gases because they have a stronger radiative effect than CO_2 on a per molecule basis. To achieve a complete GHG accounting, we included net CO_2 fluxes, CH_4 uptake, N_2O emissions, and the CO_2 costs of N fertilizer production in the calculation of GHG_{net}. A series of simulations were performed to investigate how climate, land management, vegetation cover, and soil properties interact to control GHG_{net}, crop yields, and N losses from gaseous emissions and leaching.

DAYCENT simulations of dryland agricultural loam and sandy loam soils suggest that the majority of N gas losses are in the form of nitric oxide (NO_x) and that the proportion of total fluxes that are in the form of N_2O increases as soil particle size decreases (Chapter 4). Dinitrogen (N_2) emissions were a minor proportion of total N gas losses (< 12%) and increased as soil texture became finer. No till winter wheat/fallow rotations had higher simulated N_2O emissions than conventional till winter wheat fallow because soil water contents were higher under no till. However, three year no till winter wheat/corn/fallow rotations had lower N_2O emissions than the conventional till winter wheat/fallow system. Irrigated corn had the highest N_2O emissions due to decreased water stress and high N fertilizer additions and range grass had the lowest. For equivalent dryland cropping rotations, total N gas emissions were higher in the sandy loam soil while N_2O emissions were higher in the loam soil.

GHG_{net} was calculated for different land management scenarios for a dryland agricultural site in Colorado and a Corn Belt site in Indiana. Long term simulations agreed with general data from these regions showing SOC decreases resulting from conversion of the native system to agriculture. Allowing land to revert to the native condition resulted in C sequestration and reduced N_2O emissions but it is unlikely that a significant amount of land will be removed from agricultural production (Chapter 5). Conversion of dryland agriculture to intensive irrigated agriculture leads to increased N_2O emissions but this is more than compensated for by high rates of CO_2 storage in soil due to increased NPP (Chapter 5). However, it is unlikely that more water will be made available for agriculture in the arid west. Simulations also suggest that land use change can sequester C in SOM without necessarily reducing crop yields. Conversion to no till in the corn belt should result in substantial C sequestration and have minor effects on N_2O emissions and crop yields (Chapter 5).

Reduction of the fallow period and conversion to no till in unison are predicted to result in increased crop yields and decreased GHG_{net} in dryland agricultural systems (Chapter 6). Conversion to no till conserves soil water and allows for reduction of the fallow period. No till increased SOC because tillage enhances the decomposition process. Reduction of the fallow period increases SOC because during the fallow season the land is kept free of vegetation so there are minimal inputs to SOC but decomposition continues so SOC is depleted. Also, N_2O emissions per unit of N fertilizer applied are predicted to be lower when the fallow period is reduced because during the fallow period mineral N released from decomposition is available for microbial processes that result in N gas emissions because competition from plant uptake is minimal.

Regional DAYCENT simulations for a portion of the US Great Plains show that substantial GHG_{net} reductions can be achieved by changing land management without reducing crop yields (Chapter 7). Large portions of land that are currently in winter wheat cropping could show large reductions in GHG_{net} upon conversion to no till rotations that decrease the summer fallow period. The minority of the cropped land in the Great Plains that is currently used for irrigated agriculture would show modest reductions in GHG_{net} upon conversion to no till.

Corn/soybean simulations for a site in the Midwestern US showed higher grain yields and lower total N gas losses from clay loam than sandy loam soil (Chapter 8). N_2O

emissions were higher from the clay loam. Conversion to no till led to slightly lower yields and higher N leaching for both soil types. But no till also has substantial gains in SOC and lower N gas losses. Split fertilizer application increased crop yields and decreased N leaching and N gas losses. In sum, the substantial gains in SOC under no till more than compensate for slightly lower yields and higher leaching (Chapter 8). Including split fertilizer application would increase the positive and decrease the negative effects of no till.

This research demonstrated that the effects of land use changes on N_2O and CH_4 fluxes are important and CO_2 fluxes should not be the only concern from a GHG perspective. Also, the effects of land management on reactive N inputs to the biosphere via N gas and N leaching losses should be considered. In the larger context, land use change also alters the water cycle, the albedo of land cover, and other factors that influence local and regional climate patterns. This research represents an extension of the total N approach advocated by Galloway and Cowling (2002). In addition to considering the effect of human activity on the overall N cycle, the impacts of GHG emissions and land use change should be accounted for when comparing different land management scenarios.

The DAYCENT model is a valuable tool to help assess the impact of different land uses on important ecosystem parameters. Ideally, DAYCENT should be integrated with economic models to improve cost/benefit analysis for competing land management options. Strengths of DAYCENT include ease of use, driving data is readily available, and extensive model testing. Weaknesses include substantial errors in a minority of sites and failure to simulate spatial and topological impacts.

REFERENCE

Galloway, J.N. and E.B. Cowling. 2002. Reactive nitrogen and the world: 200 years of change. AMBIO 31: 64-71.