Modeling Carbon and Nitrogen Dynamics for Soil Management

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CHAPTER 8

Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model[1]

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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

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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 from biological N fixation in crops, and ~25 Tg 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; for example, 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 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 such models are likely to be overly generalized and cannot represent the heterogeneity characteristic of most real-world systems. DAYCENT (Kelly et al., 2000; 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 are compared to demonstrate the validity of DAYCENT. Finally, an application of the model is presented 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 can also 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^- leaching, 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., 2000) 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 to >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 is 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 nonlinearly 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.

DAYCENT includes sub-models for plant productivity, decomposition of dead plant material and SOM, soil water and temperature dynamics, and trace gas fluxes (Figure 8.1). Plant growth is limited by temperature, water, and nutrient availability. Carbon and nutrients are allocated among leaf, woody, and root biomass based on vegetation type. Transfer of C and nutrients from dead plant material to the soil organic matter and available nutrients pools is controlled by the lignin concentration and C:N ratio of the material, abiotic temperature/soil water decomposition factors,

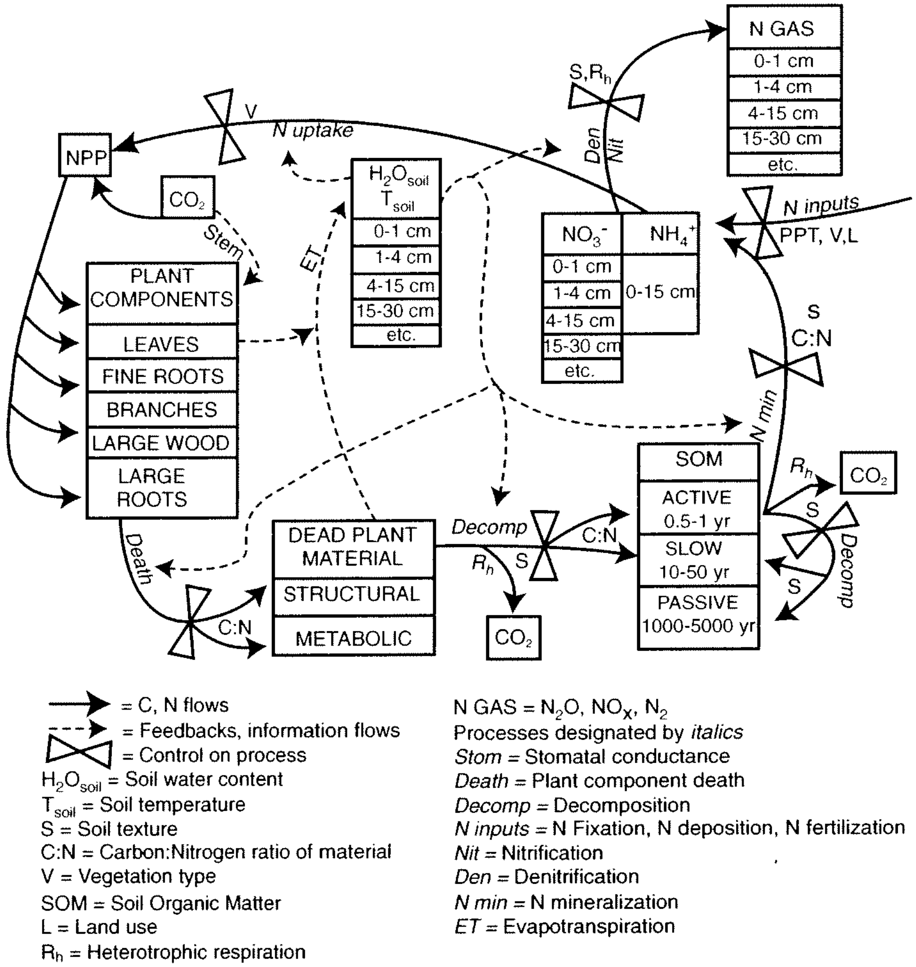


Figure 8.1 Conceptual diagram of the DAYCENT ecosystem model.

and soil physical properties related to texture. Detrital material with low C:N ratios and low proportions of lignin (metabolic) goes to the active SOM pool. The active SOM pool has a rapid turnover time (0.5 to 1 yr) and includes microbial biomass and the highly labile by-products of microbial metabolism. Structural detritus, characterized by high C:N ratios and high lignin contents, flows to the slow SOM pool. The slow SOM pool has intermediate turnover rates (10 to 50 yrs) and includes the microbial by-products that are moderately resistant to further decomposition. Products of SOM decomposition that are extremely resistant to further breakdown make up the passive SOM pool, which has very slow turnover (1000 to 5000 yr). A lower proportion of decomposing SOM is respired as CO_2 and more organic matter is retained in stable forms due to chemical and physical protection as soils become finer textured. The available nutrient pool (NO_3^-, NH_4^+, P, S) is supplied by decomposition of SOM, biological N fixation, and external nutrient additions such as fertilization and N deposition. The rate of nutrient supply from decomposition is determined by the proportions of SOM in the respective pools, and soil water, temperature, and texture. NO_3^- is distributed throughout the soil profile while NH_4^+ is modeled for the 0–15 cm layer only. Available nutrients are distributed among soil 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 Sub-model

The DAYCENT plant production sub-model (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 sub-model (Figure 8.2) divides plant biomass among grain, shoot, and root compartments, while the forest sub-model 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.

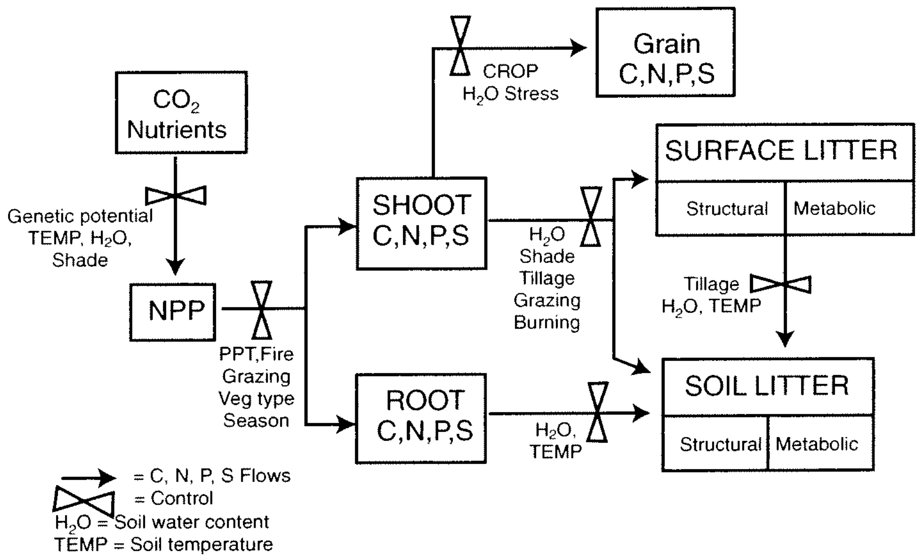


Figure 8.2 The grassland/crop growth sub-model of DAYCENT.

Land Surface Sub-model

The land surface sub-model of DAYCENT (Parton et al., 1998) simulates water flow through the plant canopy, litter, and soil (Figure 8.3), 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 is: 0–1 cm, 1–4 cm, 4–15 cm, 15–30 cm, 30–45 cm, ..., 135–150 cm. 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 the 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 the water input rate is greater than K_{sat} (cm/s), the difference goes to surface

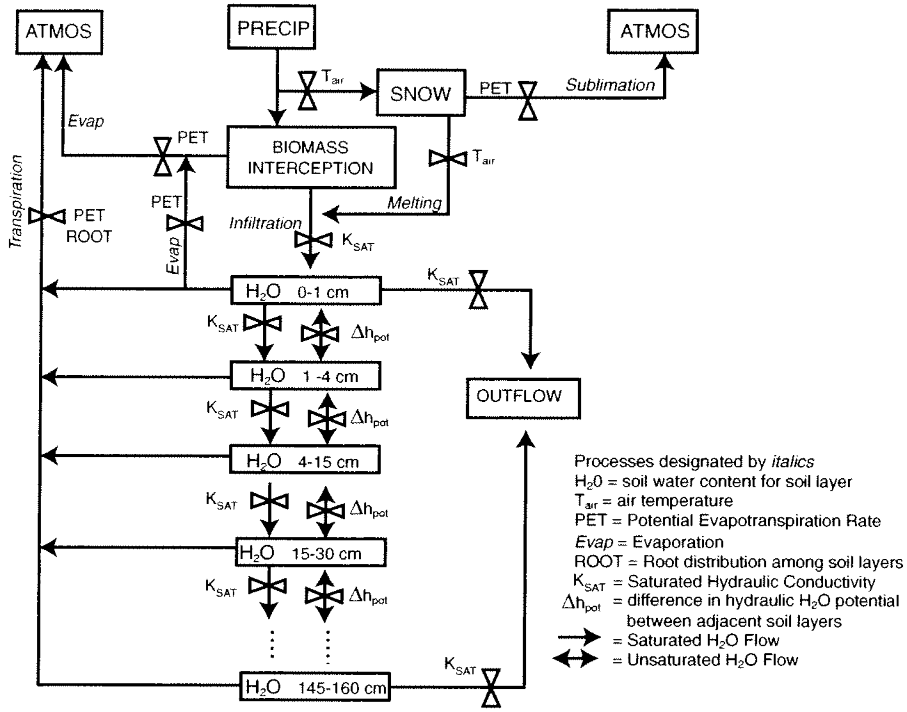


Figure 8.3 The water flow sub-model of DAYCENT.

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 sub-model (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.

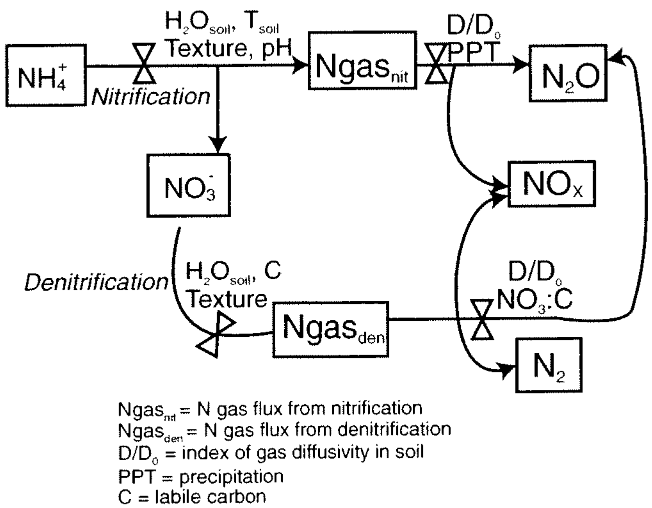


Figure 8.4 The nitrogen gas flux sub-model of DAYCENT.

N Gas Sub-model

The N gas sub-model (Parton et al., in press; Del Grosso et al., 2000) 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 8.4). 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., in press). 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 a biochemical process in which heterotrophic microbes reduce NO_3^- to NO_x, N_2O, and N_2 under anaerobic conditions. The denitrification sub-model (Del Grosso et al., 2000; Parton et al., 1996) first calculates total N gas flux from denitrification (N_2 + N_2O) and then uses a N_2:N_2O ratio function to infer N_2O and N_2 emissions (Figure 8.4). 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 that 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 N_2:N_2O ratio 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., in press). 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 can 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 sub-model 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 downward 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., in press). This chapter section presents 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 g N/m^2/yr 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. First consider how well DAYCENT simulated the drivers of the N gas sub-model and then compare observed and simulated N_2O emissions.

Figures 8.5a and b 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 the high spatial heterogeneity of measured soil water content from snow drifting and melting. The model correctly simulated the trends in soil water content for the cropped soil (Figure 8.5c) but did not dry to the extent indicated by the data. Similarly, the model simulated the general trends in soil temperature (Figure 8.5d), but some data points were greatly over- or underestimated. Figure 8.6a 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 8.6b). Figures 8.6c and d 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 accurately captured the monthly and seasonal trends in N_2O emissions from the native soil, although winter season fluxes tended to be underestimated. 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 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

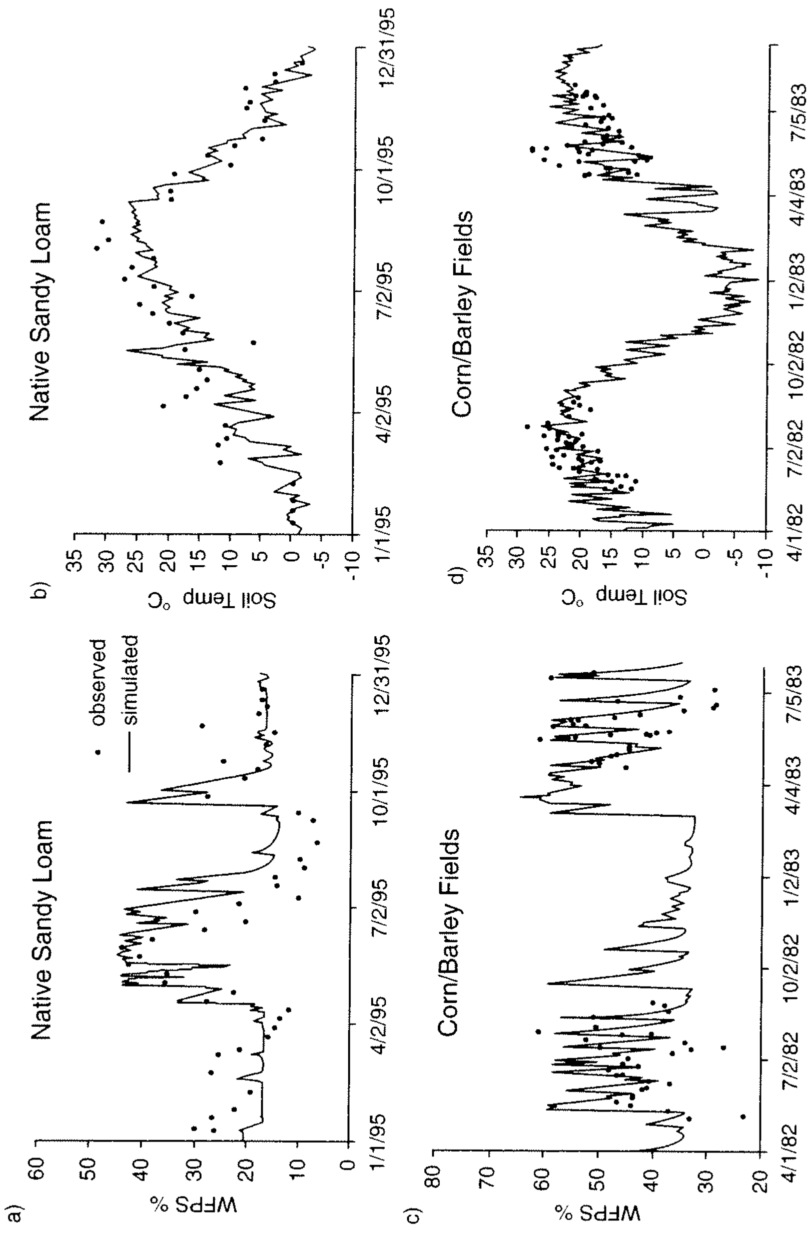


Figure 8.5 Observed and simulated values of soil water content and temperature for a native sandy loam grassland soil (a, b) and for a fertilized, irrigated field cropped with corn in 1982 and barley in 1983 (c, d).

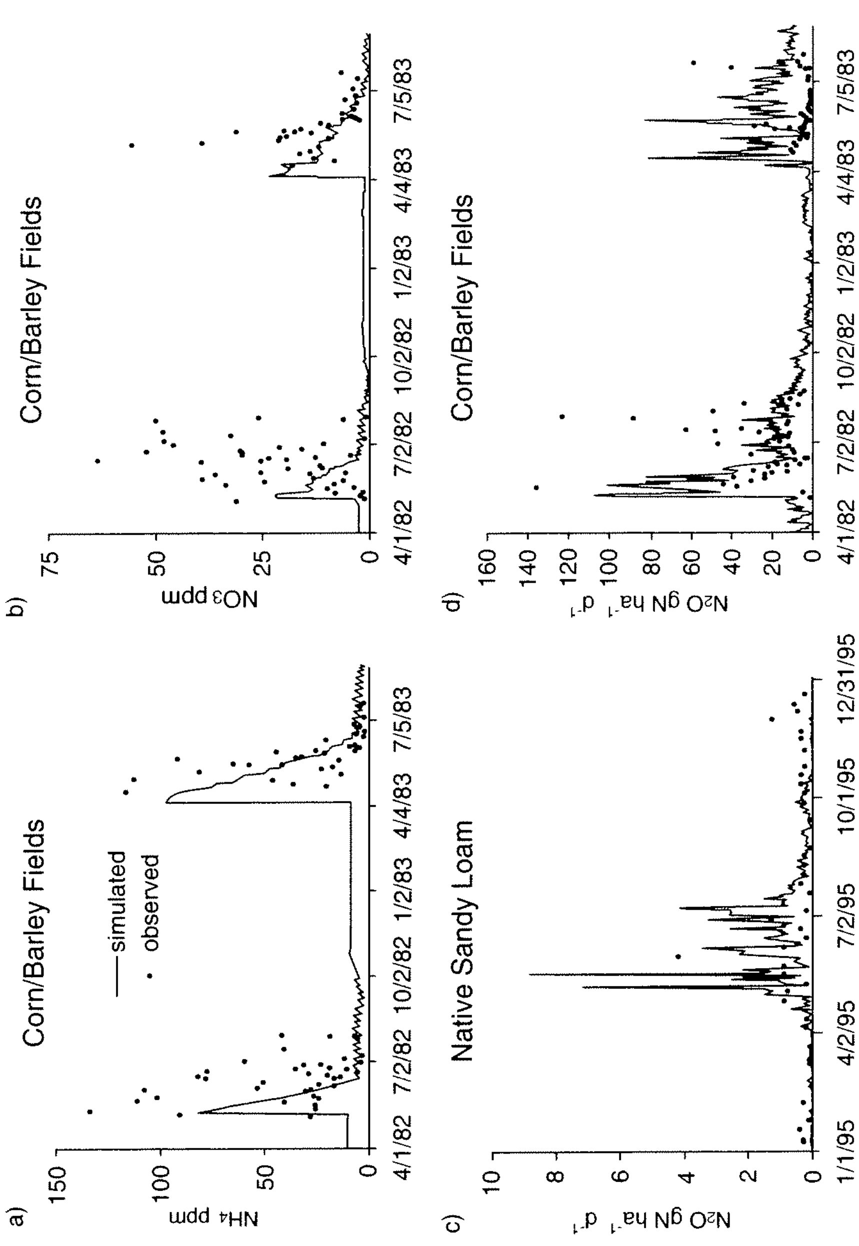


Figure 8.6 Observed and simulated values of soil nitrate and ammonium for a fertilized, irrigated field cropped with corn in 1982 and barley in 1983 (a, b). Observed and simulated N_2O gas fluxes from the native sandy loam grassland soil (c) and from the cropped soil (d).

emissions from denitrification (an anaerobic process) were not observed. The authors 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 sub-model 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 8.6c and d). 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., in press) showed that seasonal N gas fluxes were fairly well represented by the model with observed vs. simulated r^2 values of 0.29 and 0.43 for monthly N_2O and NO_x emissions, respectively, for the combined data from five 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

The authors used DAYCENT to compare the trade-offs 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/soybean rotations, each under conventional or no-till cultivation.

To compare the net greenhouse gas effect of the management options, the authors 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). The N_2O emissions were also simulated for each option, and a yearly CO_2 equivalent for N_2O gas emissions was calculated 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. The authors 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, followed by the results of the simulations for the wetter midwestern soil.

Simulation of Conventional Winter Wheat/Fallow Rotations and Six 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. 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 to 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 to 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 to 2080) of conventional till winter wheat/fallow rotations (wwct) and six alternative management scenarios (Table 8.1): 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 to 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 kg C/m^2 soil, which agrees closely with measured values (1.4 to 1.5 kg C/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 aboveground NPP were compiled for winter wheat/fallow cropping and each alternative scenario.

Figure 8.7a 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

Table 8.1 Land Management Practices Simulated by DAYCENT

Crop/Vegetation	N Addition (g N/m²/yr)	Month(s) of N Addition	Irrigation	Tillage
	Great Plains Soil			
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

Note: 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

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 8.7b). 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 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 to 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

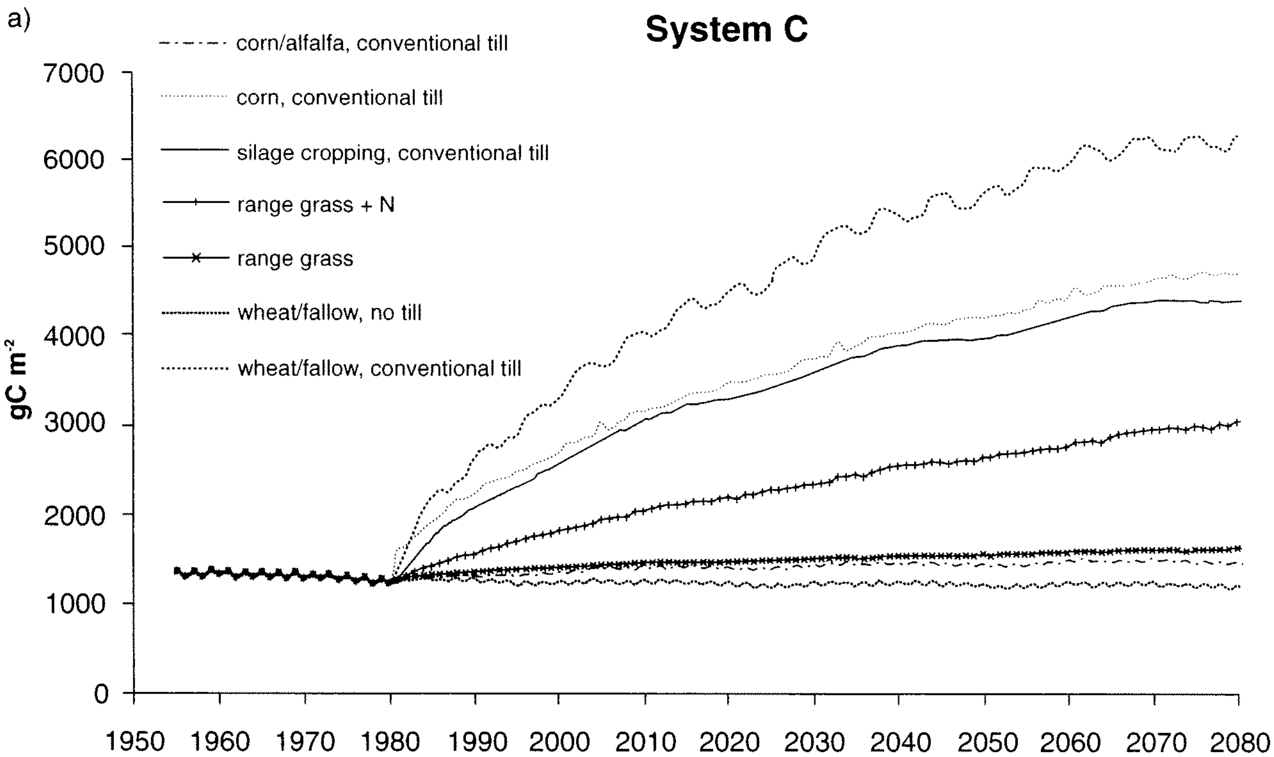
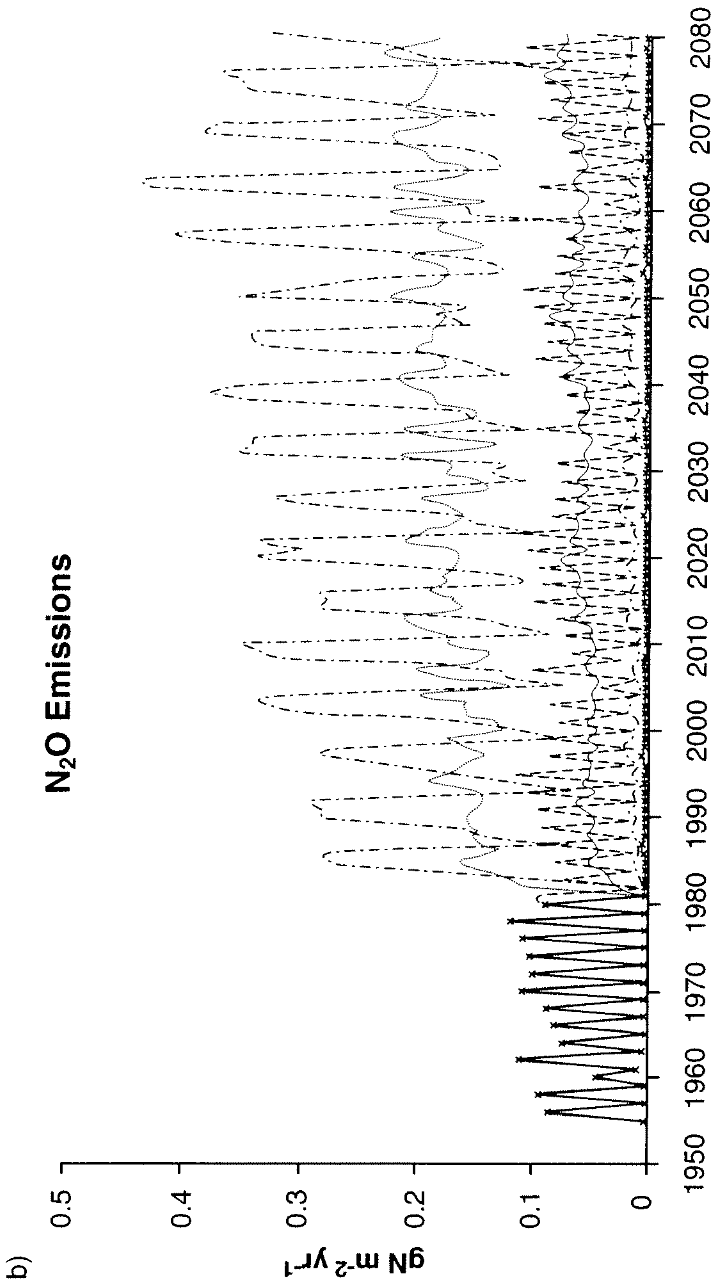


Figure 8.7 Simulated yearly changes in system C (soil C + litter C + surface organic matter C) (a); cumulative yearly N_2O emissions (b); and cumulative yearly NO_3^- leaching (c) for a Great Plains soil under conventional till winter wheat/fallow rotations and six alternative land use scenarios.



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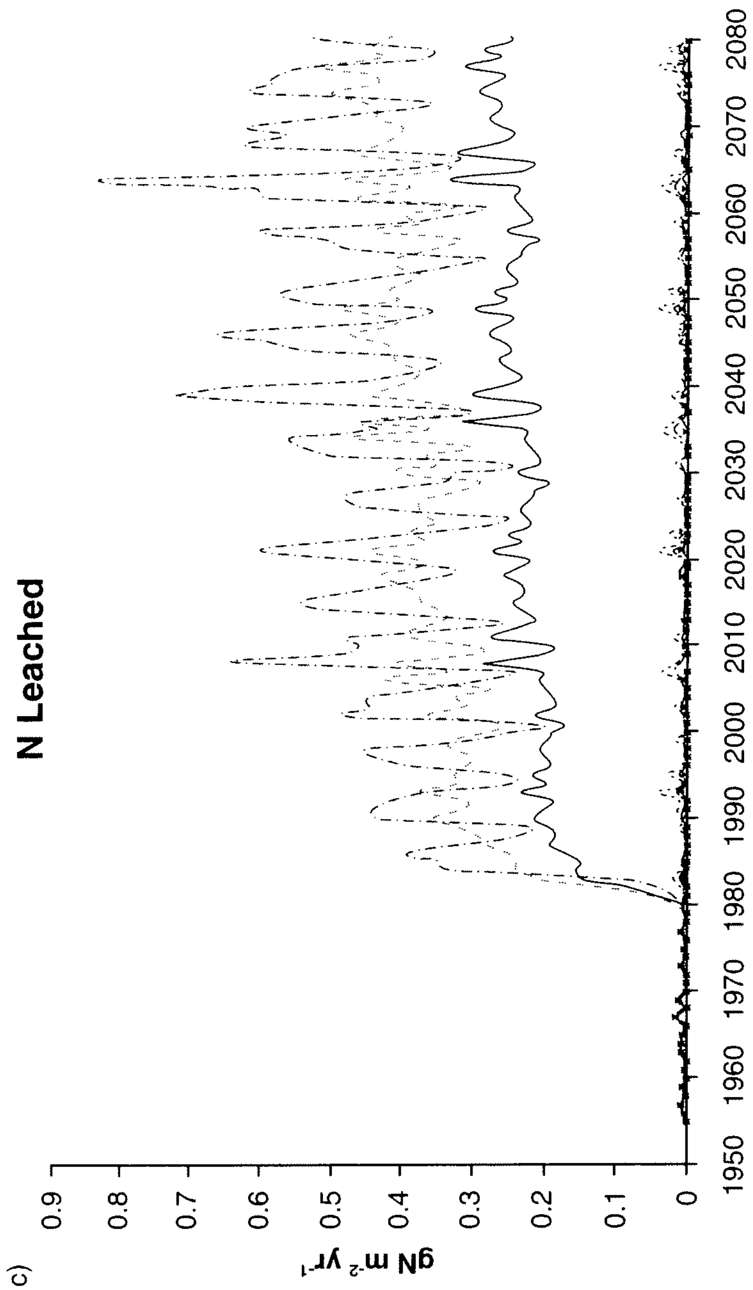


Figure 8.7 (continued).

no significant amounts of NO_3^- leaching (Figure 8.7c). 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, the output for system C (SOM C + surface organic matter C + litter C), N_2O emissions, NO_3^- leaching, and crop yields were aggregated into 25-year periods. Figure 8.8a shows the change in system C for each scenario from the perspective of the atmosphere. Thus, conversion from

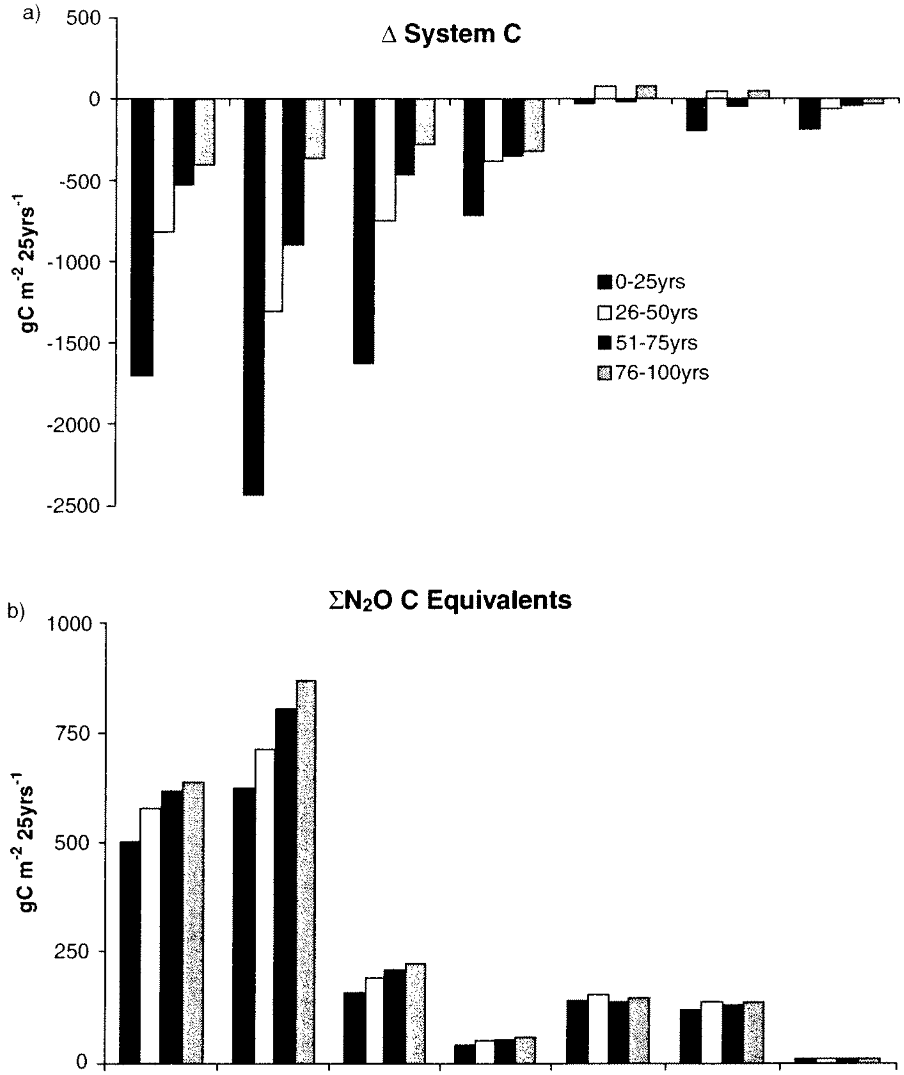


Figure 8.8 Summaries of DAYCENT simulations of changes in system C (a); cumulative CO_2-C equivalents of N_2O gas emissions (b); net C (c); and cumulative above-ground plant productivity (d) for 25-year periods of conventional tillage winter wheat/fallow and six alternative land uses.

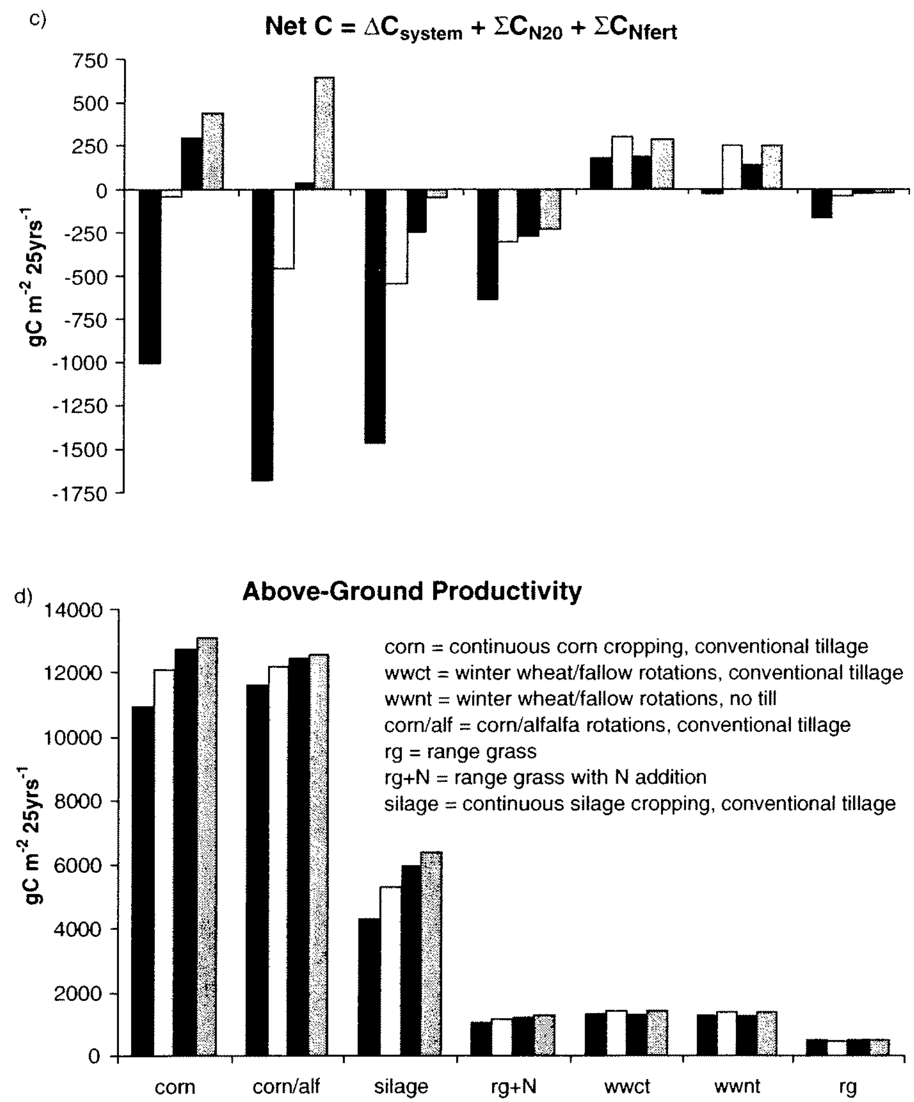


Figure 8.8 (continued).

winter wheat/fallow rotations to continuous, irrigated corn cropping resulted in an increase of ~1700 g C/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 8.8b 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 8.8c shows net C sequestration for each scenario by accounting for flows of CO_2 between the atmosphere and the soil (Figure 8.8a), the CO_2 equivalents of N_2O emissions (Figure 8.8b), 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 to 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 8.8d 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 8.7a) 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 United States. To compare the effects of tillage practices on soil C levels, N_2O emissions, crop yields, and NO_3^- leaching, the authors first performed a 100-year simulation to derive initial conditions for soil C and nutrient levels. Using a weather file for Lafayette, Indiana (mean annual precipitation = 94 cm, mean annual temperature = 10.2°C), the authors 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. Beginning 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 8.1. Fertilizer (ammonium nitrate) was added at a rate of 15 g N/m^2 in a split application (7.5 g N/m 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 g C/m^2 in 1950. Soil C then increased to ~5000 g C/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; Higgins et al., 1998). Figure 8.9a 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 8.9b and c). 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.

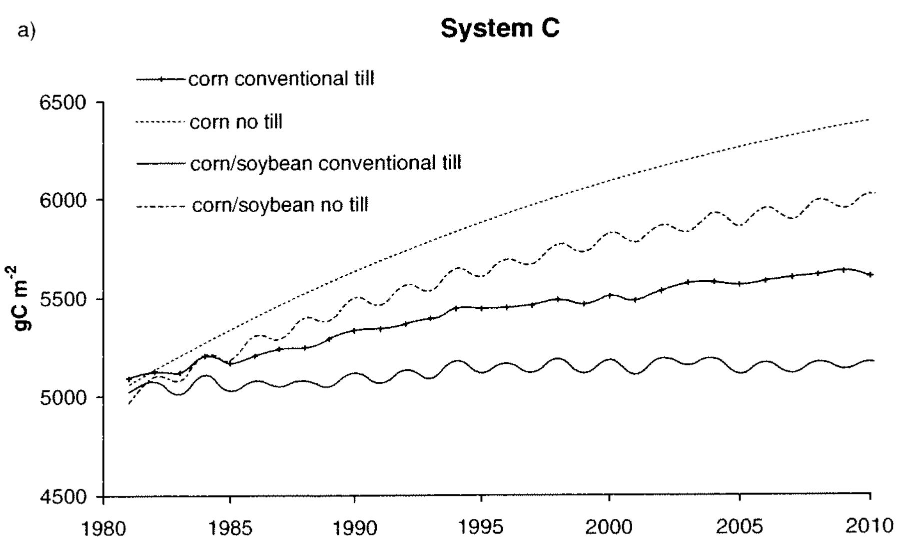


Figure 8.9 Simulated yearly changes in system C (soil C + litter C + surface organic matter C) (a); cumulative yearly N_2O emissions (b); and cumulative yearly NO_3^- leaching (c) for a midwestern soil under conventional till and no-till perennial corn and corn/soybean cropping.

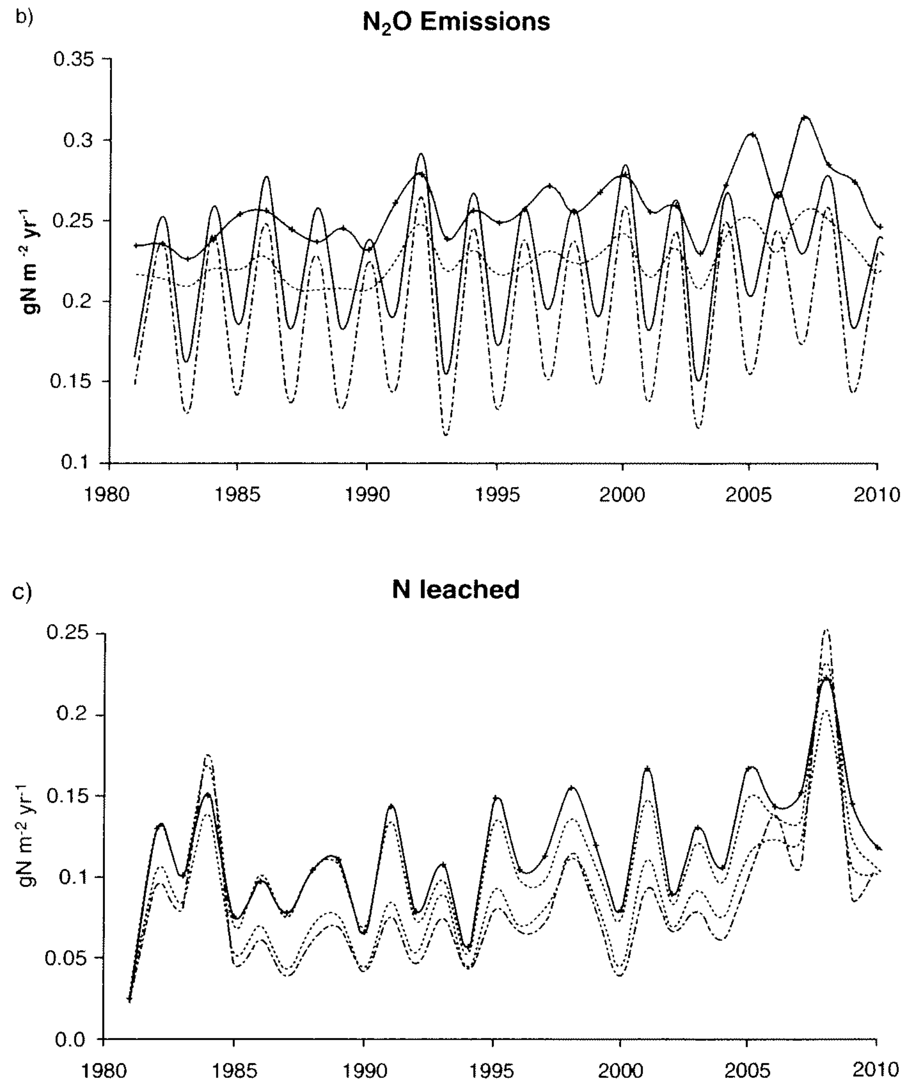


Figure 8.9 (continued).

To summarize and compare the results, the authors aggregated changes in SOM, total C equivalents for N_2O emissions, and grain yields for 10-year periods. Figure 8.10a 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 8.10b). Corn/soybean rotations emitted less N_2O than continuous corn cropping because N fertilizer was not added during the soybean year. Net C (Figure 8.10c) was calculated by summing the change in system C (Figure 8.10a), the C equivalents of the aggregated N_2O emissions (Figure 8.10b),

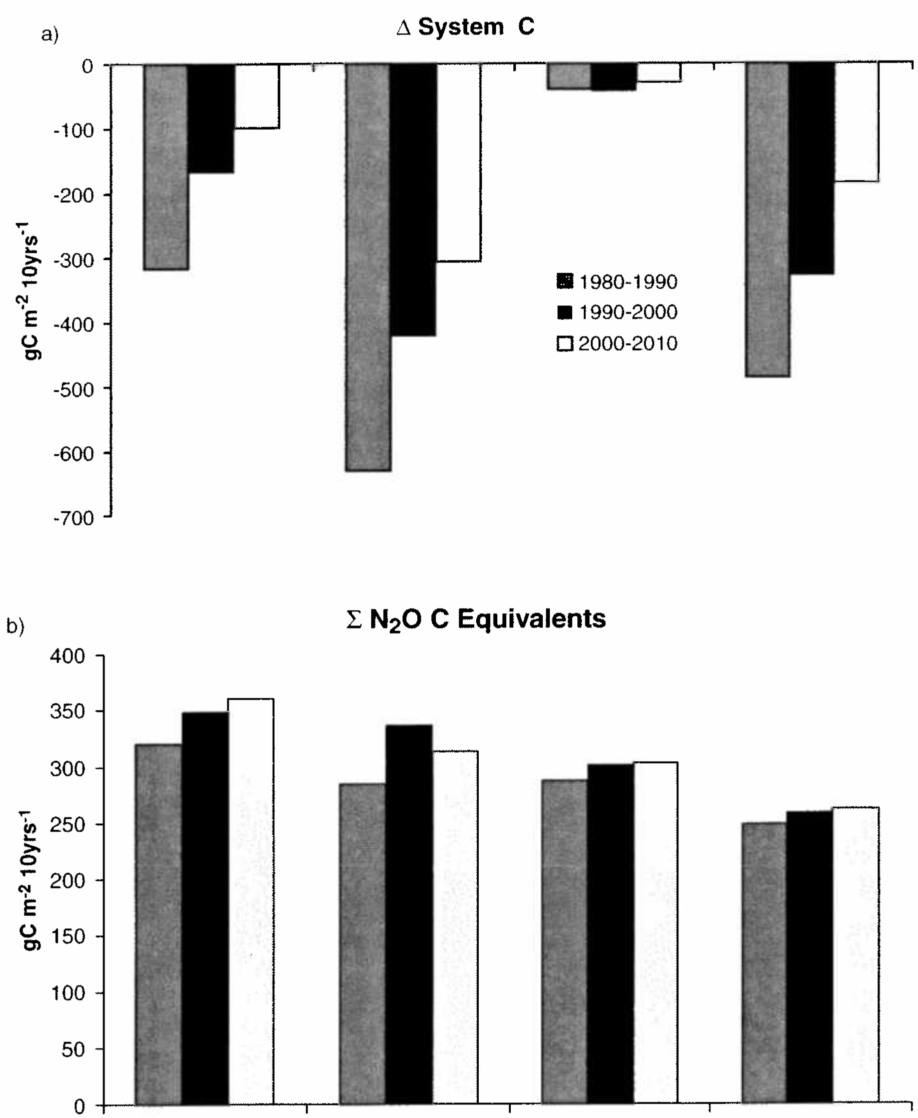
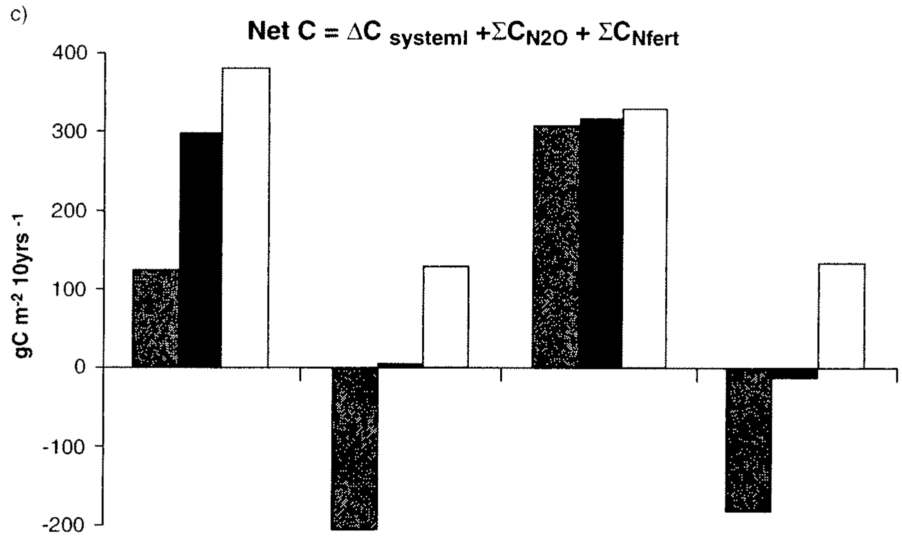


Figure 8.10 Summaries of DAYCENT simulations of changes in system C (a); cumulative CO_2-C equivalents of N_2O gas emissions (b); net C (c); and cumulative above-ground plant productivity (d) for 10-year periods of conventional till and no-till perennial corn and corn/soybean cropping.

and the CO_2 costs associated with N fertilizer production. Both no-till treatments (cnt and 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



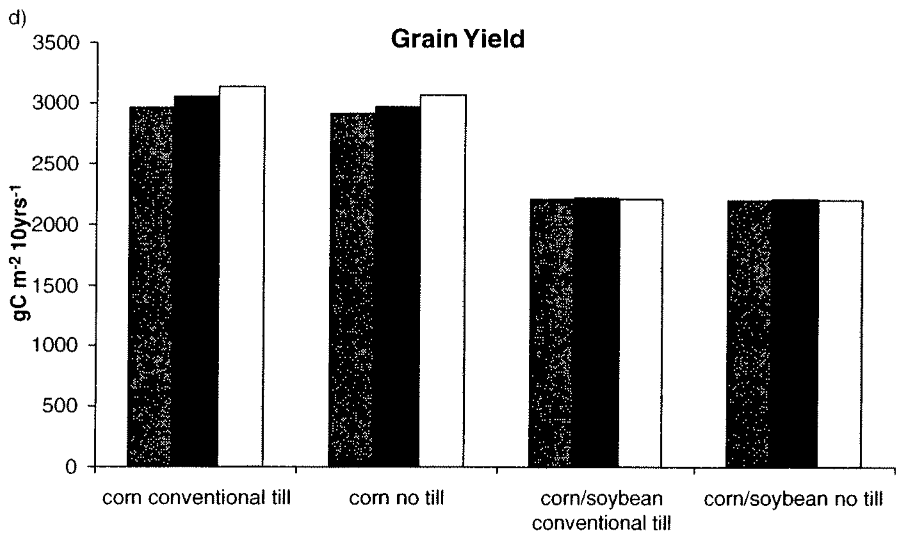


Figure 8.10 (continued).

yield (Figure 8.10d). Corn has a higher growth rate than soybeans and produces a larger grain yield than soybeans (Figure 8.10d). 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 8.10a). To summarize, DAYCENT simulations suggest that conversion to no-till in the U.S. corn belt 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

The authors 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, 100-year simulations were performed to initialize SOM and soil nutrient levels. Model results support observations of previous researchers (Higgins 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 kg C/m^2) was somewhat less than the value for the midwestern soil (5.0 kg C/m^2). Both 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 chosen for simulations was finer textured, so SOM was more likely to become stabilized than SOM in the coarser-textured Great Plains soil used for simulations. The midwestern soil also receives ~2.5 times the precipitation of the Great Plains 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 and thus 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 to 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 amounts of C upon conversion to intensive, perennial cropping provided that water for irrigation is 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 that 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. (2000), 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 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 the authors are 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 to 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.

REFERENCES

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

Bruce, J.B., M. Frome, E. Haites, H. Janzen, R. Lal, and K. Paustian. 1999. Carbon sequestration in soils. *J. Soil Water Conserv.*, 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., 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 Sci. Soc. Am. J.*, 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*, Kluwer Academic, The Netherlands, 303-311.

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

Eitzinger, J., W.J. Parton, and M.D. Hartman. In press. Improvement and validation of a daily soil temperature sub-model for freezing/thawing periods, *Soil Sci.*

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 Biol. Biochem.*, 25:1317-1329.

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

Higgins, 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 R.S. Oremland (Ed.). *Biogeochemistry of Global Change: Radiatively Active Trace Gases,* Chapman & Hall, New York, 290-316.

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: new model, verification, simulations. *J. Geophys. Res.: Atmospheres,* 105:93-100.

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,* 81:75-90.

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. Cyc.,* 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 P.A. Matson and R.C. Harriss (Eds.). *Biogenic Trace Gases: Measuring Emissions from Soil and Water,* Blackwell Scientific, Malden, MA, 1-13.

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, CO.

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. Cyc.,* 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. Cyc.,* 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,* Vol. 45, 31-53.

Parton, W.J. 1984. Predicting soil temperatures in a shortgrass steppe. *Soil Sci.,* 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 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. Cyc.,* 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, Madison, WI, 147-167.

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. Cyc.,* 10:401-412.

Parton, W.J., M. Hartman, D.S. Ojima and D.S. Schimel. 1998. DAYCENT: its land surface sub-model: 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. In press. Generalized model for NO_x and N_2O emissions from soils, *J. Geophys. Res.*

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.

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

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.

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 Sci. Soc. Am. J.*, 63:1350-1358.

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

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

Vitousek, P.M., J. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and D.G. Tilman. 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.