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Chapter 18. DAYCENT Simulated Effects of Land Use and Climate on County Level N Loss Vectors in the USA

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We describe the nitrogen (N) gas (NH_3, NO_x, N_2O, N_2) emission and NO_3 leaching submodels used in the DAYCENT ecosystem model and demonstrate the ability of DAYCENT to simulate observed N_2O emission and NO_3 leaching rates for various sites representing different climate regimes, soil types, and land uses. DAYCENT simulated seven major crops, grazing lands, and potential native vegetation at the county level for the United States. At the national scale, NO_3 leaching was the major loss vector, accounting for 86%, 66%, and 56% of total N losses for cropped soils, grazed lands, and native vegetation, respectively. NH_3 volatilization + NO_x emissions made up the majority of national N gas losses, accounting for 58%, 89%, and 86% of N gas losses from cropped soils, grazed lands, and native vegetation, respectively. However, there was considerable spatial variability in the N loss vectors, with leaching accounting for less than 20% of total N losses and NO_x + NH_3 emissions accounting for less than 50% of N gas losses in some counties. Land use area weighted mean annual N losses were 43.9 (SD = 26.8) and 12.3 (SD = 22.2) kg N/ha for cropped/grazed and native systems, respectively. Area weighted mean annual N gas losses were 11.8 (SD = 4.8) and 5.4 (SD = 2.1) kg N/ha for cropped/grazed and native systems, respectively. Total N losses and NO_3 leaching tended to increase as N inputs and precipitation increased, and as soils became coarser textured. Total N gas losses also increased with N inputs and as soils became coarser textured, but N_2O and N_2 made up a larger portion of N gas losses as soils became finer textured and as precipitation increased.

1. INTRODUCTION

Flows of 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; Vitousek et al., 2002) 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 counterpart, nitrite (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). Nitrate (NO_3) leaching is a major N loss vector for agroecosystems which contributes to aquatic eutrophication and can pose a risk to human health. Human activity has profoundly altered fixation rates of atmospheric N_2, emission rates of N_2O and NO_x to the atmosphere, and losses of NO_3 to waterways. 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 (Vitousek et al., 1997; Smil, 1999; Galloway et al., 2003). 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). Agriculture is a primary source of NO_3 leaching into waterways (Howarth et al., 1996; Goolsby et al., 1999; Boesch et al., 2001).

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 fluxes 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, 2003; Grant, 2004). 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 and NO_3 leaching to demonstrate the validity of DAYCENT. Lastly, we use DAYCENT to compare annual N gas (NH_3, NO_x, N_2O, and N_2) and NO_3 leaching losses associated with different land uses, soil textures, and water inputs.

2. DAYCENT MODEL DESCRIPTION

DAYCENT (Parton et al., 1998; Kelly et al., 2000; 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 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. 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. Recent improvements in the plant submodel include the ability to make seed germination a function of soil temperature and plant harvest/senescence a function of accumulated growing degree days. 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 byproducts of decomposition that turnover in approximately 1 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) byproducts 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

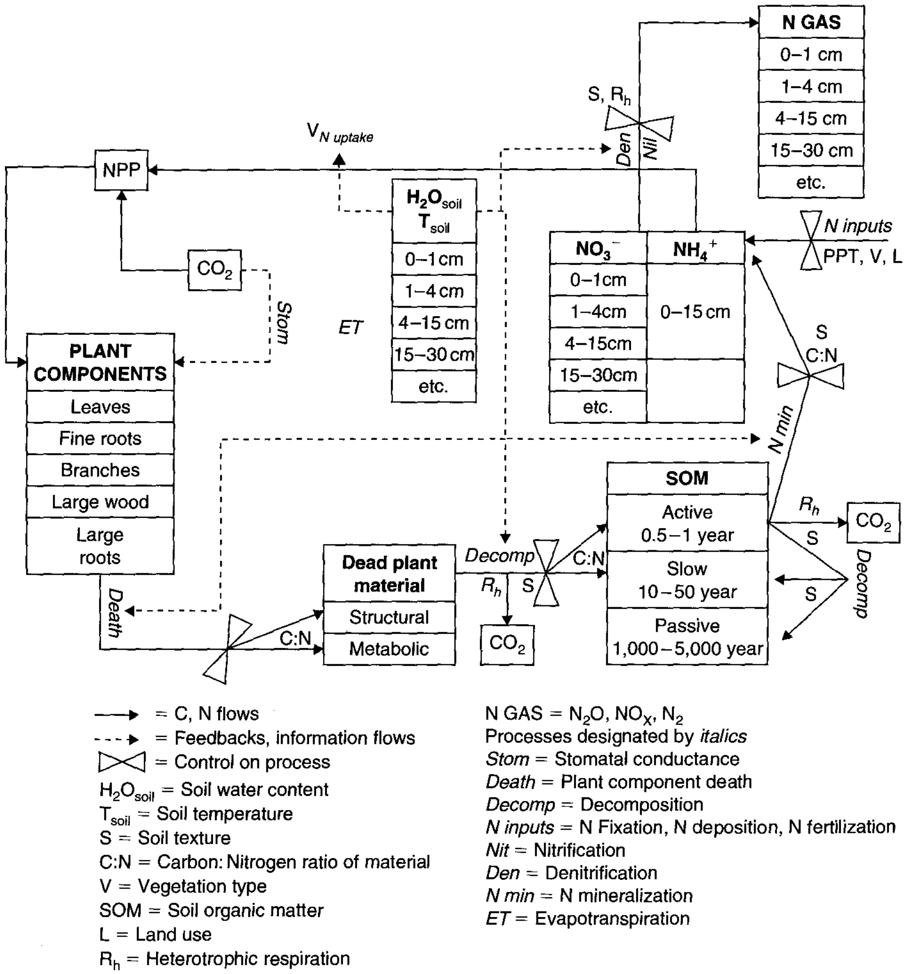

Figure 1. Conceptual diagram of the DAYCENT ecosystem model. Modified from Del Grosso et al. (2001).

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., 2000). Saturated water flow is simulated down the soil profile on days that it rains, snow melts, or a field is irrigated. Unsaturated flow is simulated on all days that do not have water inputs sufficient to saturate the profile and can be up or down the profile depending on matric and gravitational potentials. If water inputs are sufficient, given a soil texture specific saturated hydraulic conductivity, excess water will not enter the profile and is assumed to be runoff. Coarse textured soils are assumed to have higher saturated conductivity than finer textured soils. As saturated conductivity increases, surface runoff decreases and water and NO_3 flow down the profile increase. Soil water and dissolved NO_3 that exit the deepest soil layer simulated are assumed to be leached into ground water or the subsoil but the model does not simulate lateral transfer of water or nutrients. 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 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, 2001). Nitrification rates increase linearly with soil NH_4^+

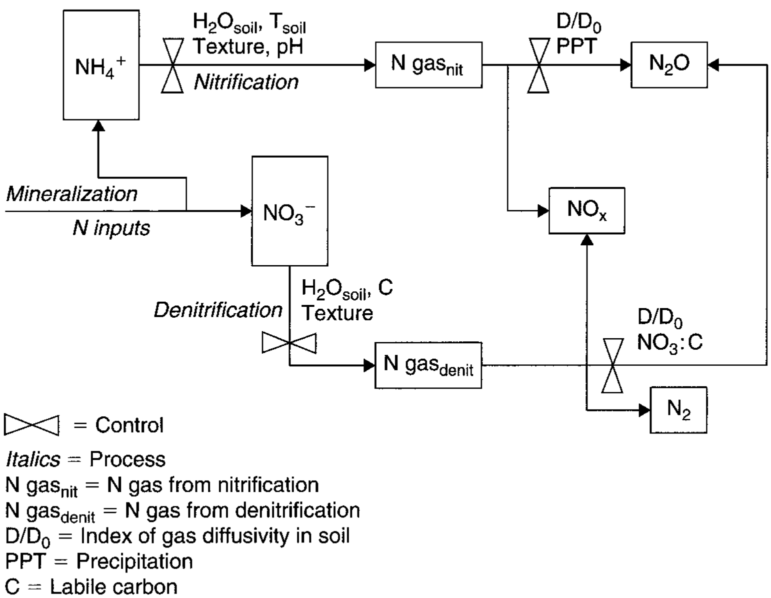

Figure 2. The N gas flux submodel of DAYCENT. Modified from Del Grosso et al. (2001).

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., 2000). 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_0, 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_0 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., 2001). 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_0 is high and decreases to a minimum of ~1 as D/D_0 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_0) and mainly to denitrification under anaerobic conditions (Linn and Doran, 1984; Davidson, 1993). 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 current version of DAYCENT includes canopy absorption of soil NO_x emissions as a function of leaf area index. The model also predicts that, other factors being equal, NO_x emissions from cultivated soils will be lower than emissions if the soil was not cultivated. Plowing tends to distribute nutrients and organic matter to deeper depths, whereas nutrients tend to concentrate close to the surface in uncultivated soils. Consequently, nitrification is more likely to occur deeper in cultivated than undisturbed soils, NO_x liberated must diffuse through more layers before emitting from the soil surface, and the likelihood of NO_x being reduced to N_2O increases. 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 (Hutchinson et al., 1993; Martin et al., 1998; Smart et al., 1999). 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 10.

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 downward if there is not enough NO_3^- and NH_4^+ available to supply the potential N gas emissions for a particular time step. NH_3 volatilization is simulated less mechanistically than the other N gas species. A soil texture specific portion of N excreted from animals is assumed to be volatilized (more volatilization as soils become coarser), and a plant specific portion of harvested or senesced biomass N is assumed to be volatilized.

3. DAYCENT MODEL VALIDATION

We first summarize results of previous tests of the DAYCENT model for various natural and managed systems and then present results of tests with the latest version of the model. 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. (2001) 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.

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. (2001) showed that the model represented 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., 2000). The snow melt submodel has been improved and winter season soil water contents are now better represented.

Table 1 lists data sources that were used to test the ability of the latest version of DAYCENT to simulate N_2O emissions and NO_3 leaching. Various crops with different tillage practices and fertilization intensities are represented. Data from plots in grasslands and deciduous forest are also included in the data set. N_2O emissions from intensively cropped systems can exceed those of native systems by an order of magnitude or more so N_2O values were log transferred. DAYCENT simulated mean annual N_2O emissions and NO_3 leaching well, with r^2 values of 0.88 and 0.98, respectively (Figure 3). We emphasize that although the latest version of DAYCENT was modified to represent plant growth and soil water flows more realistically, the model is still much better at simulating differences in mean fluxes for treatments within sites and across sites than it is at matching the daily patterns

Table 1.
Sources of data used for model testing.

Location	Crops/vegetation	N Loss Vector Evaluated	References
Iowa	Fertilized fallow/soybean	N_2O	Bremner et al. (1981)
Michigan	Corn, soybean, wheat conventional till and no till, alfalfa, deciduous forest	N_2O	Robertson et al. (2000)
Nebraska	Wheat/fallow, sod	N_2O	Kessavalou et al. (1998)
Colorado	Wheat/fallow	N_2O	Mosier et al. (1997)
Colorado	Irrigated corn, barley	N_2O	Mosier et al. (1986)
Colorado	Irrigated corn, soybean, conventional till and no till	N_2O	Mosier et al. (2006)
Tennessee	Corn, no till	N_2O	Thornton and Valente (1996)
Ontario	Corn	N_2O	Grant and Pattey (2003)
Colorado	Shortgrass steppe	N_2O	Mosier et al. 1996, 1997
Iowa	Corn, soybean	NO_3 leaching	Jaynes et al. (2001)
Wisconsin	Corn	NO_3 leaching	Andraski et al. (2000)
Wisconsin	Corn, potato	NO_3 leaching	Stites and Kraft (2001)

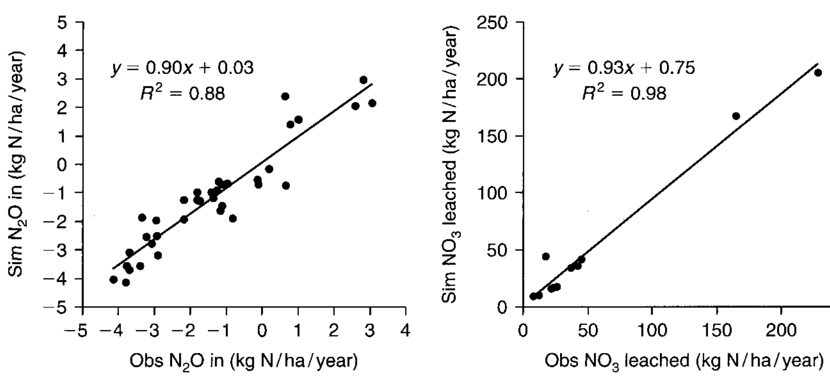

Figure 3. Comparison of simulated versus observed annual N_2O gas emission and NO_3 leaching rates from various field experiments listed in Table 1.

in emissions exhibited by observed data. See Del Grosso et al. (2005) for further model validation results and comparisons of DAYCENT simulated N_2O emissions and NO_3 leaching with emissions and leaching calculated using IPCC (1997) methodology.

4. DAYCENT MODEL APPLICATION

4.1. Model Simulations

National DAYCENT simulations of potential native vegetation and different cropping systems in the United States were used to investigate the effects of land use, soil texture, and climate on N loss vectors. DAYCENT is currently being used to estimate N_2O emissions from agricultural soils for the US GHG inventory (EPA, 2005). Potential native vegetation, major crops [corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.) hay, other hay, sorghum (*Sorghum bicolor* L. Moench), and cotton (*Gossypium hirsutum* L.)], and grazed lands were simulated at county level resolution. Counties that reported less than 40 ha of agricultural land were not simulated. Daily maximum/minimum temperature and precipitation were acquired from DAYMET (Thornton et al., 1997, 2000; Thornton and Running, 1999; http://www.daymet.org/). For each county, DAYMET climate from the 1 km^2 cell that was closest to the geographical center of cropped land was used to drive DAYCENT. Soil texture data required by DAYCENT were obtained from the State Soil Geographic Database (STATSGO, http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/). The dominant STATSGO map unit that intersected the geographical center of cropped land in each county was used to drive DAYCENT. Native vegetation was based on the Kuchler (1993) potential natural vegetation map. Before simulating modern cropping systems, SOM and mineral N (NH_4^+, NO_3^-) pools were initialized for the different counties by simulating ~1,800 years of native vegetation followed by ~200 years of historical cropping practices. Data for crop management (e.g., timing and type of cultivation and fertilization, crop rotation schedules) were obtained from various sources (EPA, 2005). Separate simulations of 2,003 years of native vegetation were performed so that N losses under modern agriculture could be compared with those from native vegetation. DAYCENT outputs for annual N loss vectors were saved for the years 1990–2003. For details on how the county resolution simulations were performed see EPA (2005) or Del Grosso et al. (2006).

Annual DAYCENT outputs were processed to obtain national totals for N loss vectors and to obtain county level area weighted N losses that account for the areal distribution of cropped and grazed lands. N losses for each crop in each county were calculated by multiplying DAYCENT outputs for NO_3 leaching, NH_3 volatilization, and NO_x, N_2O, and N_2 emissions in units of gN/m^2 by National Agricultural Statistics Service (NASS) reported county level crop area data (http://www.nass.usda.gov:81/ipedbcnty/sso-mapc.htm). N losses for grazing lands in each county were calculated by multiplying DAYCENT outputs for the N loss vectors by grazing land area estimates derived from the National Resources Inventory (NRI; USDA, 2000). N losses for potential native vegetation were obtained by multiplying the DAYCENT outputs for native vegetation by the sum of cropped and grazed land areas simulated in each county. Total county level N losses for cropped/grazed lands were obtained by summing losses from all the crops and grazed land simulated in each county. National totals for N loss vectors were obtained by summing loss vectors for each county simulated. Temporal mean annual national N loss vectors for 1990–2003 were calculated from the annual national totals.

County level crop/grazed land area weighted means were calculated from the DAYCENT outputs and from NASS reported county level crop area data and NRI grazing land data. That is, the area weighted means account for the land areal distribution of major crops and grazed land in each county. Temporal mean annual outputs for 1990–2003 were calculated from the area weighted NO_3 leaching and N gas outputs. Mean outputs for potential native vegetation were calculated in a similar manner except it was not necessary to include area weighing because 100% of the cropped and grazed land in each county was assumed to be uniformly covered with native vegetation.

4.2. Model Results

DAYCENT simulations show that at the national scale, the majority of total N losses are due to NO_3 leaching, especially for cropped systems (Table 2). Although leaching is not the primary loss vector under native vegetation for most of the counties in the arid west, leaching is the major loss vector in wetter areas, where N inputs tend to be higher (Figure 4); hence leaching dominates at the national scale. Consideration of the processes that are responsible for soil N losses explains why most of the losses from mesic soils are from leaching. When nitrification occurs, the majority of NH_4 N is converted to NO_3, with typically less than 10% of the N lost as $NO_x + N_2O$. Once NO_3 is available in mesic soil, it is more likely to be taken up by plants or leached than denitrified to N_2O or N_2 because leaching is a physical process that is primarily a function of NO_3 availability, soil hydraulic properties,

Table 2.
Fractions for N loss vectors at the national scale for crops, pastures, and potential native vegetation simulated by DAYCENT.

	Cropped Lands	Grazed Lands	Native Vegetation
N Leaching and N Gas Losses Compared to Total N Losses			
NO_3 leached/N loss total	0.86	0.66	0.56
N gas/N loss total	0.14	0.34	0.44
N Gas Species Compared to Total N Gas Losses			
NH_3 volatilization/N gas	0.27	0.69	0.46
NO_x/N gas	0.31	0.19	0.39
N_2O/N gas	0.24	0.04	0.10
N_2/N gas	0.18	0.07	0.04

soil profile depth, and water inputs. Denitrification, on the other hand, is a biological process that is limited by labile C availability, soil O_2 status, and enzyme kinetics. Consequently, a single large rainfall event can leach more N below the rooting zone than is lost from denitrification during an entire year or more. Spring season snow melt events can also contribute to leaching losses because plant demand for N is low during the nongrowing season and NO_3 can accumulate in soil.

DAYCENT predicts that as N inputs increase, the proportion of total N losses that are due to NO_3 leaching also increases (Table 2). N limitation and N cycling explain this trend. N is most limiting in native systems, less limiting in grazed systems (due to forage legumes and grazing enhanced N mineralization), and least limiting in cropped systems. As N becomes more limiting, NO_3 made available from nitrification is more likely to be taken up by plants and hence less likely to be leached. Also, NO_3 is a larger portion of total N inputs in cropped compared to native or grazed systems. Some synthetic fertilizers applied to crops contain NO_3 whereas the vast majority of mineral N available in grazed or native systems is in the form of NH_4 released from decomposition and urine from grazing animals and the only external source of NO_3 is from atmospheric deposition, which tends to be much lower than fertilizer inputs.

Total N losses were over three times higher and NO_3 leaching almost five times higher for cropped/grazed land than native systems on a per area basis (Table 3). Native systems have smaller N leaching because inputs are low (Figure 4a) and N is more limiting. Leaching is higher for cropped/grazed systems due to high N inputs (Figure 4b), particularly synthetic fertilizers, and less than optimal synchrony between N availability in soil and plant nutrient demand. Standard deviations relative to means are high for all the N loss vectors, especially for leaching and N_2 gas

Table 3.
Temporal (1990–2003) and area weighted means and standard deviations of DAYCENT simulated N loss vectors for cropped agricultural soils in the United States assuming potential native vegetation coverage and reported cropped and grazed land areas.

	Mean (kg N/ha/year)		Standard Deviation (kg N/ha/year)	
N Loss Vector	Native	Cropped/grazed	Native	Cropped/grazed
NO_3 leached	6.90	32.12	21.49	23.83
NH_3 gas	2.49	6.26	1.29	2.64
NO_x gas	2.11	3.46	1.48	1.69
N_2O gas	0.55	1.36	0.31	0.82
N_2 gas	0.23	3.46	0.62	1.69
Total N losses	12.27	43.95	22.21	25.81

emissions, because the processes that control N losses respond nonlinearly to the controls on the processes. For example, water inputs must exceed a threshold before large leaching events are possible. Similarly, the anaerobic conditions that facilitate denitrification and N_2 emissions respond nonlinearly to soil water content which must exceed a threshold before significant N_2 emissions will occur.

Figure 5a shows total N losses per unit area assuming potential native vegetation coverage and for the present day areal distribution of major crops and pasture land at the county level. Total N losses are driven by interactions between N inputs, precipitation, and soil texture. For most native systems, the primary source of external N inputs is atmospheric deposition so inputs tend to increase with precipitation (Figure 4a). Consequently, N losses are greater in the eastern, wetter half of the United States, than the arid west. N losses are higher in the Southeast compared to the Northeast and upper Midwest for two reasons: soils tend to be coarser in the Southeast so NO_3 leaching is facilitated and rainfall tends to decrease along a south to north gradient in the eastern half of the United States. One caveat is that our simulation of native vegetation represents pre-settlement conditions that do not account for N inputs associated with industry and transportation. In reality, atmospheric N inputs are higher in the Northeast and near the Great Lakes than the Southeast because population density is higher and industry is more concentrated.

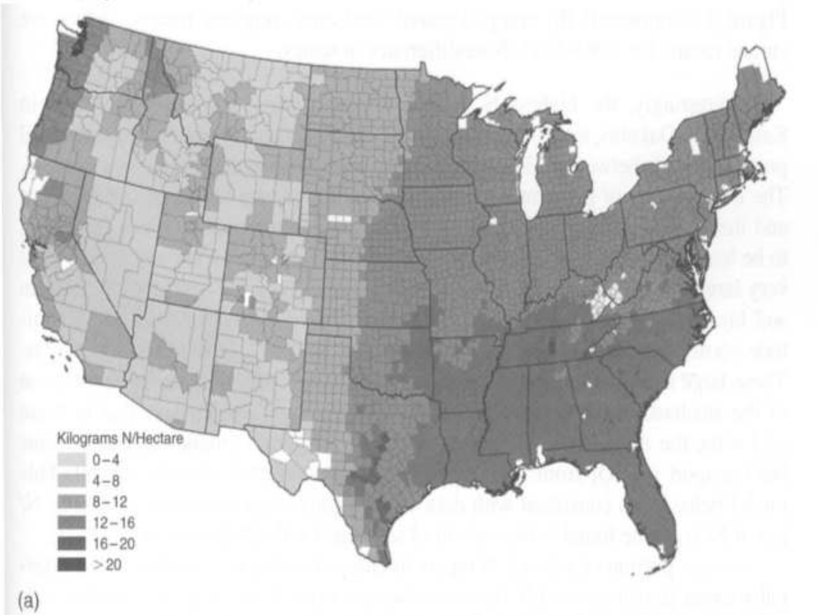

Figure 4. DAYCENT N inputs from atmospheric deposition and biological N-fixation for (a) native potential vegetation.

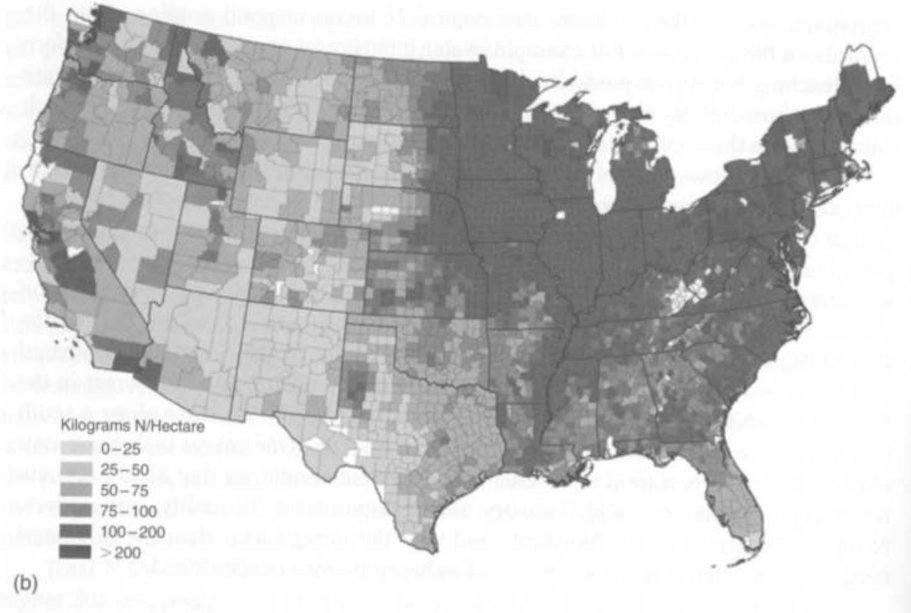

Figure 4 (Continued) (b) cropped/grazed land area weighted means. Values are annual means for 1990–2003. Note difference in scales.

Interestingly, the highest N losses for native vegetation are in counties in Kansas, the Dakotas, and Colorado. The soils are loams in these areas, mean annual precipitation is between ~35 and 70 cm, and native vegetation class is grassland. The combination of moderate rainfall, soils with moderate hydraulic conductivity, and the relatively shallow rooting depth of grasses compared to trees allows NO_3 to be leached below the rooting zone, but not out the bottom of the soil profile until very large rainfall events occur. That is, NO_3 can build up for many (>10) years in soil layers below the grass rooting zone until a rainfall event of sufficient magnitude occurs to saturate the entire soil profile and leach NO_3 from the bottom layers. These large leaching values are only exhibited in a minority of the counties because of the stochastic nature of large precipitation events. We emphasize that in these arid soils, the model is not simulating NO_3 leaching into groundwater or streams but transport of NO_3 from the deepest soil layer simulated into the subsoil. This model behavior is consistent with data showing that large amounts (>1,000 kg N/ha) of NO_3 can be found in the subsoil of some arid soils (Walvoord et al., 2003).

A large portion of mineral N inputs to cropped and grazed lands is from external sources (fertilizers and N-fixation) whereas most of the mineral N made available in native systems is supplied internally from decomposition of organic matter. Consequently, N losses from cropped/grazed lands are high in areas that grow crops which require high N inputs. DAYCENT predicts high N losses in the Corn Belt,

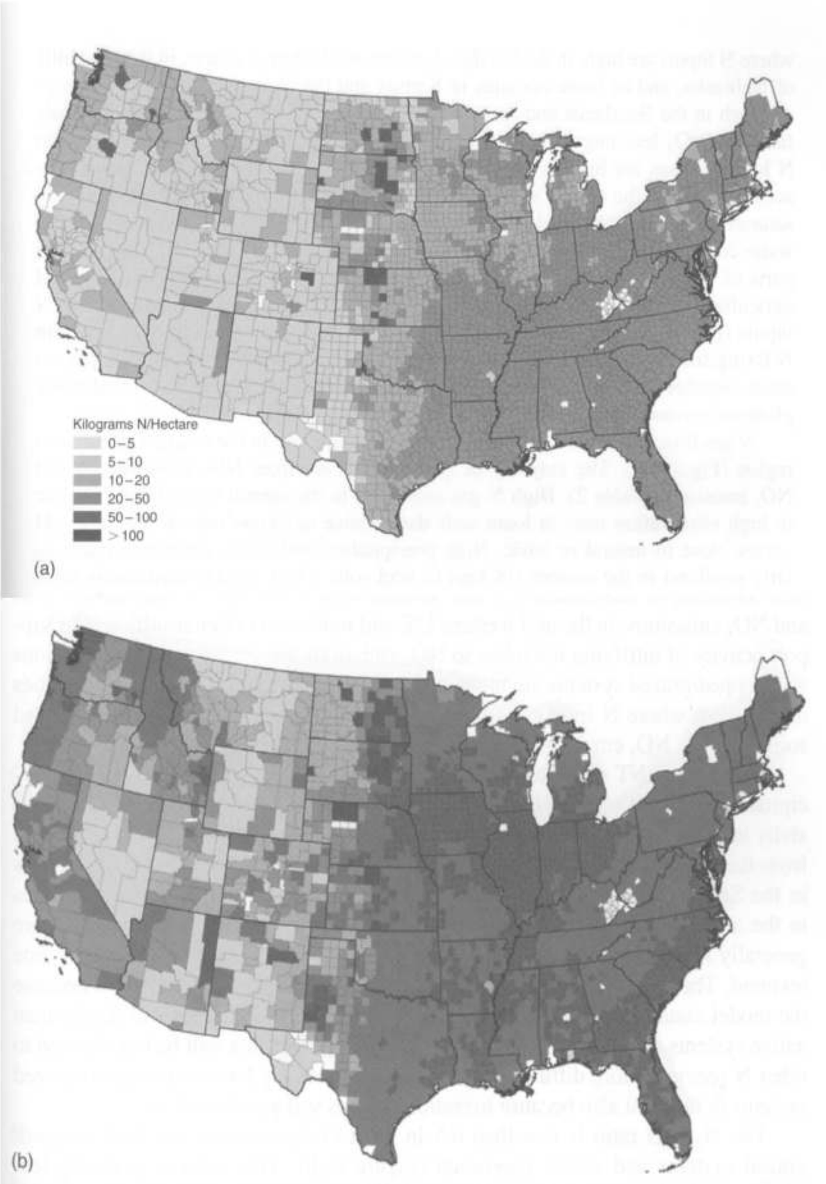

Figure 5. DAYCENT simulated county level mean N losses from NO_3 leaching and N gas emissions (NH_3, NO_x, N_2O, N_2) for (a) potential native vegetation and (b) cropped/grazed land area weighted means. Values are annual means for 1990–2003.

where N inputs are high, in the Southeast, where soil texture is coarse, in the sand hills of Nebraska, and in some counties in Kansas and the Dakotas (Figure 5b). Losses are high in the Southeast and the sand hills of Nebraska because these sandy soils facilitate NO_3 leaching and NH_3 and NO_x gas losses. Similar to native vegetation N losses, losses are high in some counties in Kansas and the Dakotas due to NO_3 accumulating in the deeper soil layers until a rainfall event of sufficient magnitude saturates the soil profile and leaches NO_3 into the subsoil. N losses per unit area in some counties in the western US are on par with losses in the central and eastern parts of the country because of high N and water inputs associated with irrigated agriculture. Some counties in the Northeast and Great Lakes regions have high N inputs (Figure 4b) but moderate N losses (Figure 5b). This is due to N inputs from N fixing forage legumes in pastures making up a large portion of total N inputs in these counties and the model assuming that fixed N is more efficiently cycled in the plant-soil system than N from fertilizer so losses are lower.

N gas losses under native vegetation cover are highest in the central Great Plains region (Figure 6a). The majority of N gas losses are from NH_3 volatilization and NO_x emissions (Table 2). High N gas emissions in the central Great Plains are due to high nitrification rates in loam soils that receive moderate rainfall and have pH values close to neutral or basic. High precipitation and forest vegetation (particularly conifers) in the eastern US lead to acid soils which inhibit nitrification rates and NO_x emissions. In the arid western US, soil moisture is often insufficient to support activity of nitrifying microbes so NO_x emissions are not large. N gas emissions for cropped/grazed systems are highest in the Corn Belt and some irrigated counties in the west, where N inputs are high, and in the Southeast where coarse textured soils facilitate NO_x emissions from nitrification and NH_3 volatilization (Figure 6b).

The DAYCENT simulated NO_x/N_2O ratio is largely a function of land use, precipitation, and soil texture (Figure 7a,b). The model assumes that as soil gas diffusivity increases, conditions become more oxic, and NO_x is more likely to be emitted from the soil surface than to be reduced to N_2O. Well drained, coarse textured soils in the Southeast have high gas diffusivity so the ratio is high and many counties in the arid west have high diffusivity because soils tend to be dry. The ratios are generally low in the Midwest and Northeast where soils tend to be medium to fine textured. The ratio is higher for native vegetation than agricultural systems because the model assumes that N is distributed with cultivation to deeper soil depths than native systems so it is more likely that NO_x from nitrification will be transformed to other N species before diffusing from the soil. Ratios are lower for cropped/grazed systems in the west also because irrigation reduces soil gas diffusivity.

The N_2/N_2O ratio is less than 0.5 in most of the counties for both cropped/grazed systems and native vegetation (Figure 8a,b). This ratio is generally low because soil saturation is required to maintain the anaerobic conditions that are necessary for complete reduction of more oxidized N species to N_2. Additionally, labile C must be available to support denitrification which is responsible for N_2 emissions. The ratio is high for some fine textured soils in Texas, California, and along the

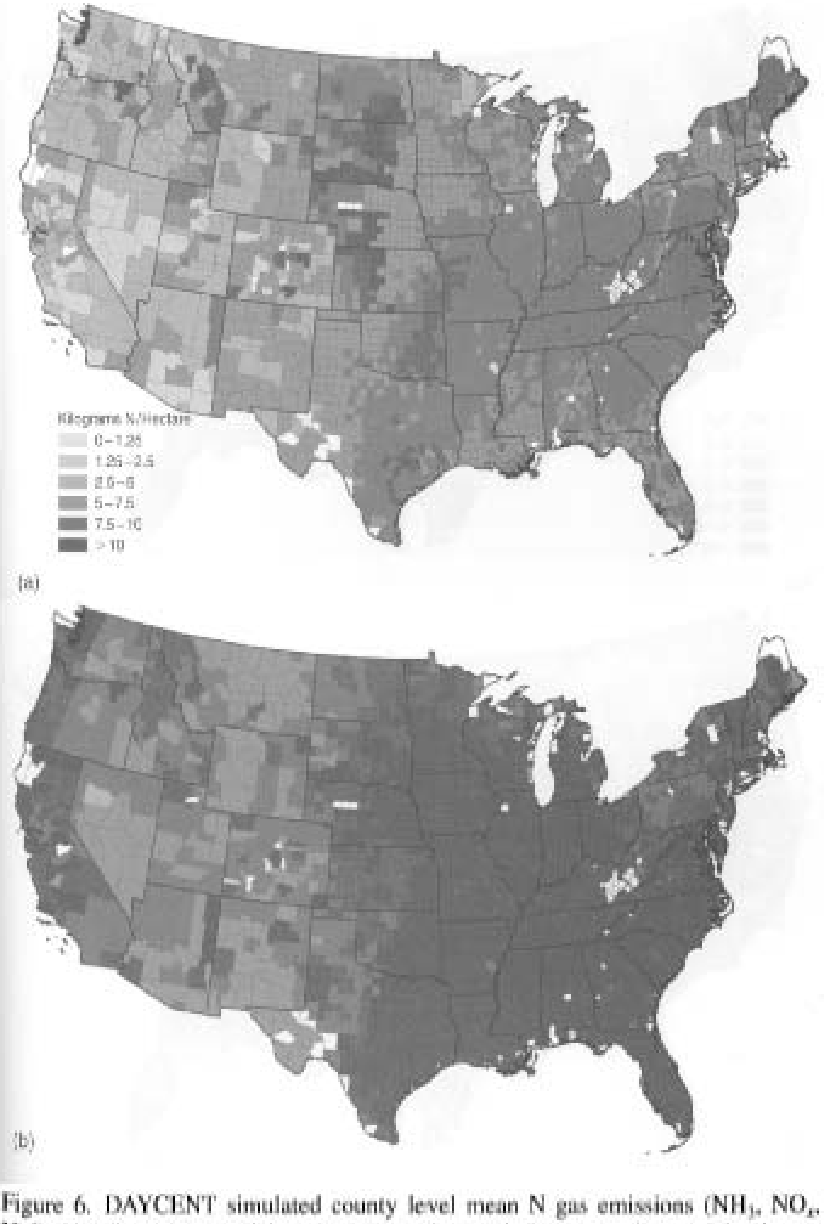

Figure 6. DAYCENT simulated county level mean N gas emissions (NH_3, NO_x, N_2O, N_2) for (a) potential native vegetation and (b) cropped/grazed land area weighted means. Values are annual means for 1990–2003.

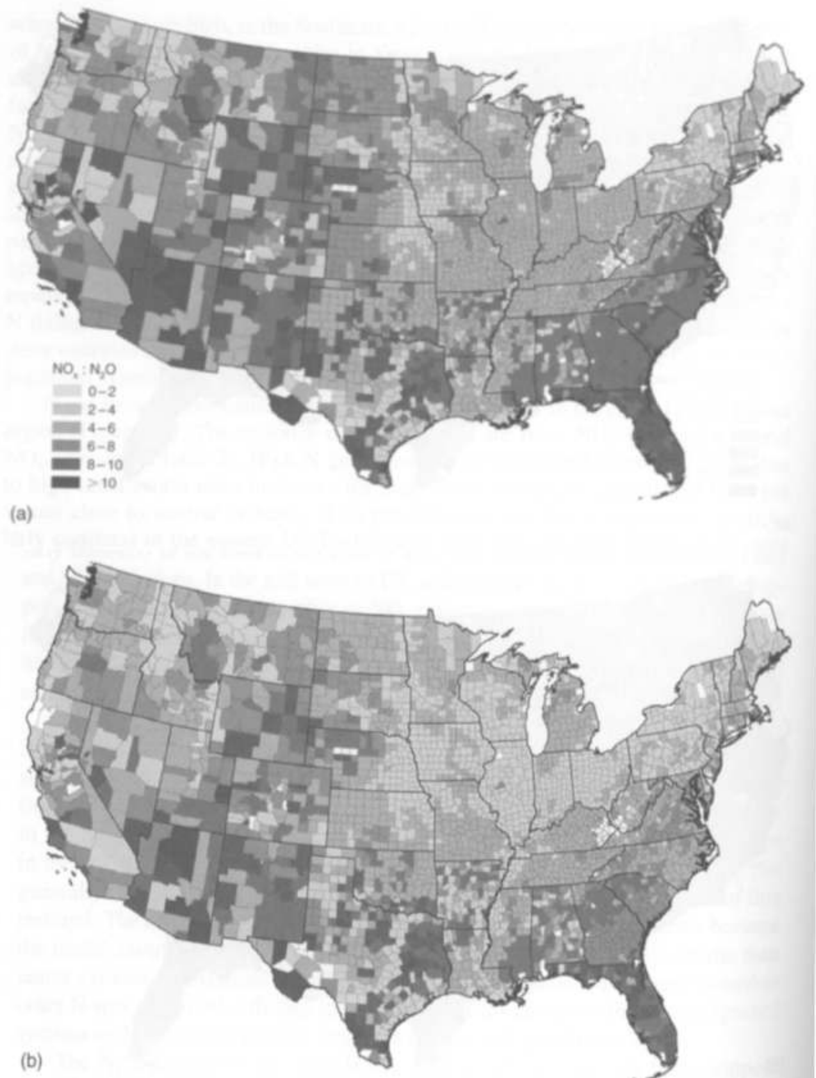

Figure 7. DAYCENT simulated county level mean NO_x/N_2O ratios for (a) potential native vegetation and (b) cropped/grazed land area weighted means. Values are annual means for 1990–2003.

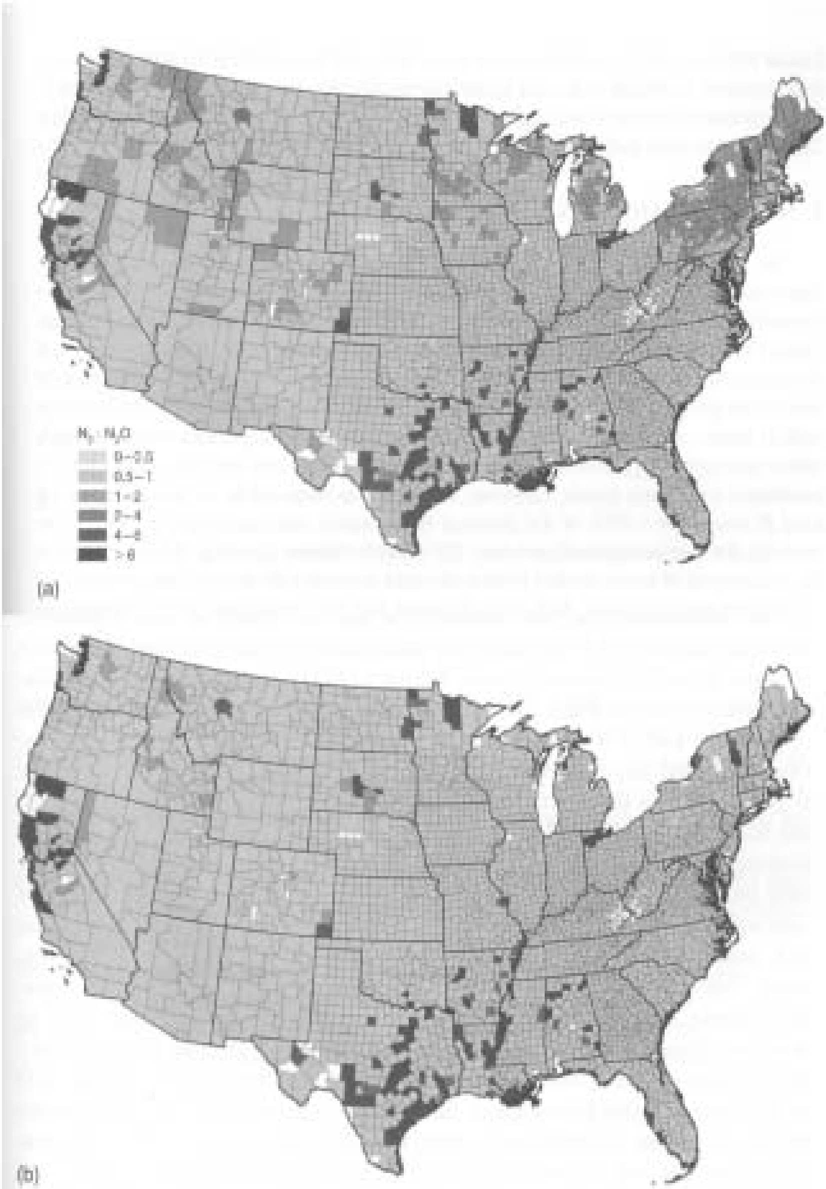

Figure 8. DAYCENT simulated county level mean N_2/N_2O ratios for (a) potential native vegetation and (b) cropped/grazed land area weighted means. Values are annual means for 1990–2003.

Lower Mississippi. Denitrification is more likely to be prevalent in poorly drained fine textured soils that maintain anaerobic microsites. It can also be high in some northern counties where melting of surface soil layers while deeper layers remain frozen can saturate soils and enhance denitrification.

5. SUMMARY AND CONCLUSIONS

We have described the DAYCENT ecosystem model and shown that annual N_2O emissions and NO_3 leaching can be reliably simulated for some managed and native systems. The model was used to explore how land use, precipitation, and soil texture impact total N losses and N gas emissions at the national scale using county level resolution simulations of cropped lands, grazed land, and native vegetation. Total N losses and the proportion of total losses due to NO_3 leaching both tended to increase with N inputs. At the national scale, NO_3 leaching was the major loss vector for both native and cropped/grazed systems because both N inputs and leaching are positively correlated with water inputs. However, leaching was responsible for less than half of total N losses for ~50% of the counties under native vegetation and ~15% of the counties for cropped/grazed systems. The counties where leaching did not make up the majority of N losses tended to be in the arid western half of the United States.

At the national scale, NH_3 volatilization and NO_x emissions were responsible for more than 84% of N gas losses for grazed and native systems and about 58% of N gas losses for cropped systems. Similar to NO_3 leaching, there was considerable variability, for example, NH_3 volatilization + NO_x emissions were responsible for less than half of N gas emissions in ~3% of counties under native vegetation. Coarse textured soils tended to have both higher NO_3 leaching losses and higher N gas losses than finer textured soils. Large pores in coarse textured soils facilitate water infiltration and flow so leaching is enhanced. Large pores also allow air exchange so O_2 is sufficient to support nitrification, the process primarily responsible for soil NO_x emissions. Volatilization of NH_3 excreted by grazing animals is also higher for coarse compared to fine textured soils. In contrast to leaching and NO_x losses, N_2O and N_2 emissions tended to increase as soils became finer textured. 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 N_2 emissions are relatively insensitive to soil texture for loam and coarser textured soils and the N_2/N_2O ratio was greater than one only in some counties with clay loam and finer textured soils. Total N gas losses decreased as soil texture became finer because NO_x and NH_3 emissions decreased and these gases formed a large portion of total 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 and leaching losses from the system.

Simulations show that N losses from soils respond nonlinearly to controls and that interactions among controls are important. We conclude that N losses from soils are strongly dependent on land management but that generalizations based solely on soil N and water inputs are likely to be limited because soil texture, soil C levels, and plant demand for nutrients are also important.

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