Global Scale DAYCENT Model Analysis of Greenhouse Gas Emissions and Mitigation Strategies for Cropped Soils

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Abstract

Conversion of native vegetation to cropland and intensification of agriculture typically result in increased greenhouse gas (GHG) emissions (mainly N_2O and CH_4) and more NO_3 leached below the root zone and into waterways. Agricultural soils are often a source but can also be a sink of CO_2. Regional and larger scale estimates of GHG emissions are usually obtained using IPCC emission factor methodology, which is associated with high uncertainty. To more realistically represent GHG emissions we used the DAYCENT biogeochemical model for non-rice major crop types (corn, wheat, soybean). IPCC methodology estimates N losses from croplands based solely on N inputs. In contrast, DAYCENT accounts for soil class, daily weather, historical vegetation cover, and land management practices such as crop type, fertilizer additions, and cultivation events. Global datasets of weather, soils, native vegetation, and cropping fractions were mapped to a 1.9° x 1.9° resolution. Non-spatial data (e.g., rates and dates of fertilizer applications) were assumed to be identical within crop types across regions. We compared model generated baseline GHG emissions and N losses for irrigated and rainfed cropping with land management alternatives intended to mitigate GHG emissions. Reduced fertilizer resulted in lower N losses, but crop yields were reduced by a similar proportion. Use of nitrification inhibitors and split fertilizer applications both led to increased (~6%) crop yields but the inhibitor led to a larger reduction in N losses (~10%). No-till cultivation, which led to C storage, combined with nitrification inhibitors, resulted in reduced GHG emissions of ~50% and increased crop yields of ~7%.

Keywords: global change, greenhouse gas mitigation, ecosystem modeling, agriculture

1. Introduction

Agricultural soils are responsible for the majority of anthropogenic nitrous oxide (N_2O) emissions (Mosier and Kroeze, 2000) and over half of methane (CH_4) emissions (IPCC, 2001). Nitrous oxide and CH_4 are important greenhouse gases (GHG's) because they have approximately 300 and 23 times (100 year time horizon), respectively, the global warming potential of carbon dioxide (CO_2) on a mass basis (IPCC, 2001). N_2O also influences ozone chemistry (Crutzen, 1981, Crutzen and Ehhalt, 1977) and CH_4 affects the oxidation state of the atmosphere (Monson and Holland, 2001). On the global scale, agricultural activities are responsible for ~14% of anthropogenic GHG emissions. There exist the potential to reduce GHG emissions from cropped soils by reducing N_2O emissions from upland crops, reducing CH_4 emissions from flooded rice paddies, and decreasing CO_2 emissions or enhancing carbon storage in soils. This paper focuses on the impacts of different mitigation strategies on N_2O and CO_2 fluxes for cropped upland soils.

Nitrous oxide is produced in soils through the biochemical processes of nitrification and denitrification (Khalil et al., 2004). Nitrification is the aerobic oxidation of ammonium to nitrate while denitrification is the anaerobic reduction of nitrate to N_2O and N_2. Agriculture practices, such as nitrogen (N) amendments (e.g. fertilizer, manure), cultivation, legume cropping, and irrigation, tend to increase N_2O production and emissions above background levels. Application of synthetic fertilizer directly increases the pool of mineral N available for nitrification and denitrification. Cultivation, particularly of soils with high organic matter levels, transfers N from the immobilized (i.e., organic) to the mineral form and thus also increases N availability for nitrification. N fixed from legume cropping can be transformed and increase the soil mineral N pool. Irrigation reduces water stress, enhances microbial activity, and contributes to soil anoxia which facilitates denitrification. These and other factors that influence mineral N supply, plant N demand, and abiotic soil conditions interact to control N_2O emissions from soils.

In addition to increasing direct soil N_2O emissions from enhanced nitrification and denitrification, agricultural practices also contribute to indirect emissions via N gas volatilization and nitrate (NO_3) leaching. N volatilization includes ammonia (NH_3) and non-N_2O N oxides (NO, NO_2) that are emitted from soils. Indirect N_2O is defined as N_2O that was emitted from a non-farm source from N that was transported from a farm in a form other than N_2O. This is caused as volatized N is deposited on non-farm soils, enters the plant/soil system, and undergoes transformations that result in N_2O emissions and as a portion of the NO_3 that is leached into aquatic systems and can be denitrified and become a source of N_2O.

Cropped soils can be sources or sinks of atmospheric CO_2 (Lal, 1999). Net CO_2 flux for soils is a function of C inputs from dead plant material and organic amendments and carbon losses from organic matter decomposition. Conventional tillage tends to enhance soil organic matter decomposition, partly because material protected in aggregates is made accessible to decomposing microbes (Six et al., 2000). Low residue crops (e.g., cotton) and leaving fields fallow reduce inputs to soils and reduce soil organic carbon (SOC) levels. Management change, e.g., growing high residue crops, reducing fallow periods, and minimizing or eliminating tillage can increase SOC levels in soils that are depleted of SOC due to many years of conventional agricultural practices (Lal, 2004; Sherrod et al., 2003).

Various strategies have been suggested to decrease GHG emissions from cropped soils. Because management options intended to reduce emissions of one GHG gas are likely to impact fluxes of other GHG's (Robertson et al., 2000) we advocate accounting for N_2O and CO_2 fluxes when comparing different strategies. The GHG mitigation options considered here are; reduction of N fertilizer applied, precision application of N fertilizer, use of nitrification inhibitors, and no-till cultivation. These options were considered for corn, soybean, and wheat, three of the major crops grown throughout the world. Reducing the amount of N fertilizer applied is expected to lead to lower N_2O emissions because N_2O emissions usually vary directly with amount of N applied (Bouwman et al., 2002). However, reducing N fertilizer is also likely to reduce crop yields and crop residue inputs to soil, which may reduce soil C levels. Precision application of fertilizer should reduce N_2O emissions because N availability is more synchronous with plant N demand, so N available for the microbial processes that result in N_2O emissions is reduced. Nitrification inhibitors directly influence nitrification rates and hence, soil N_2O emissions. Conversion to no till is expected to increase soil C, but the impact on N_2O emissions should be minor due to opposing trends. That is, as no till soils gain organic C, organic N increases also so less mineral N is available to be converted to N_2O. On the other hand, no till soils tend to be wetter than tilled soils so denitrification is facilitated.

In contrast to previous studies that typically used IPCC (1997) methodology to estimate GHG fluxes at regional and global scales, we used a process based model (DAYCENT). There are several advantages to using DAYCENT. IPCC (1997) methodology for N_2O emissions is based solely on annual N inputs. DAYCENT accounts for N inputs but also integrates other factors that influence N losses such as soil texture class, plant N demand, timing of N application, moisture stress, temperature, and organic matter decomposition rates. DAYCENT is particularly useful for evaluating mitigation options that do not involve changing N inputs whereas changing N inputs is the only strategy that IPCC (1997) methodology can address.

Using DAYCENT also provides a globally consistent methodology and allows identification of regions where different mitigation strategies show the most potential. Although using a process based model such as DAYCENT yields estimates of N_2O emissions that agree more closely with measured emissions than IPCC (1997) methodology (Del Grosso et al, 2005), running DAYCENT is more difficult and the workings of the model are less transparent. IPCC (1997) methodology can be easily implemented into a spreadsheet and emissions are directly proportional to N inputs. Large scale DAYCENT simulations, on the other hand, require programming expertise and substantial computer storage and processing capacity. Because DAYCENT accounts for interactions among the factors that influence emissions (N inputs, climate, soil, plant growth), the internal logic of the model is not highly transparent. After weighing the pros and cons of the different methodologies, we conclude that a process based model should be used if resources are available because emission estimates will be more reliable.

DAYCENT estimated emissions of N_2O and CO_2 under baseline cropping, meant to represent typical practices, and under the mitigation options considered for the years 1991-2020. Baseline cropping is defined as conventional tillage before crops are planted, one application of manure and one application of N fertilizer before planting, and harvest of grain and 75% of crop residue (i.e., leave 25% of residue in the field). Net GHG fluxes were calculated by accounting for changes in soil C, N_2O emissions, and assuming that the manufacture of each gram of synthetic N fertilizer results in emission of 0.8 gram of CO_2-C (Schlesinger, 1999). Model results were then combined with economic input and output data to derive abatement curves for GHG reductions which were included in a recent US EPA report (Gallaher et al., 2006). This paper describes how the DAYCENT simulations were performed and highlights key model results. Methods used to generate the model input data are described in detail by Stehfest (2005) and Stehfest et al. (in review).

2. **Methods**

2.1. DAYCENT model overview

DAYCENT is the daily time-step version of the CENTURY biogeochemical model (Parton et al., 1994). DAYCENT simulates fluxes of C and N among the atmosphere, vegetation, and soil (Del Grosso et al., 2001a; Parton et al., 1998). Key submodels include soil water content and temperature by layer, plant production and allocation of net primary production (NPP), decomposition of litter and soil organic matter, mineralization of nutrients, N gas emissions from nitrification and denitrification, and CH_4 oxidation in non-saturated soils. Flows of C and N between the different soil organic matter pools are controlled by the size of the pools, C/N ratio and lignin content of material, and abiotic water/temperature factors. Plant production is a function of genetic potential, phenology, nutrient availability, water/temperature stress, and solar radiation. NPP is allocated to plant components (e.g., roots vs. shoots) based on vegetation type, phenology, and water/nutrient stress. Nutrient concentrations of plant components vary within specified limits, depending on vegetation type, and nutrient availability relative to plant demand. Decomposition of litter and soil organic matter (SOM) and nutrient mineralization are functions of substrate availability, substrate quality (lignin %, C/N ratio), and water/temperature stress. N gas fluxes from nitrification and denitrification are driven by soil NH_4 and NO_3 concentrations, water content, temperature, texture, and labile C availability (Parton et al., 2001).

Model inputs are: daily maximum/minimum air temperature and precipitation, surface soil texture class, and land cover/use data (e.g., vegetation type, cultivation/planting schedules, amount and timing of nutrient amendments). Crop specific area data are also required so that DAYCENT outputs in units of C or N fluxes per square meter can be converted to national or regional level fluxes. Model outputs include: daily N-gas flux (N_2O, NO_x, N_2), CO_2 flux from heterotrophic soil respiration, soil organic C and N, NPP, H_2O and NO_3 leaching, and other ecosystem parameters. Recent improvements to the model include the ability to schedule management events daily and the option of making crop germination a function of soil temperature and harvest date a function of accumulated growing degree days.

The ability of DAYCENT to simulate NPP, soil organic carbon (SOC), N_2O emissions, and NO_3 leaching has been tested with data from various native and managed systems (Del Grosso et al., 2001b; 2002; 2005). Simulated and observed grain yields for major cropping systems in North America agreed well with data at both the site (r^2=0.90) and regional (r^2=0.66) levels (Del Grosso et al., 2005). N_2O emission data from 8 cropped sites and NO_3 leaching data from 3 cropped sites showed reasonable agreement with DAYCENT simulations yielding r^2 values of 0.74 and 0.96 for annual N_2O and NO_3 losses, respectively (Del Grosso et al., 2005). DAYCENT has also been shown to simulate N_2O emissions reasonably well (r^2>40%) for cropped soils in China (Li et al., 2005).

2.2 DAYCENT inputs, simulations, and processing of model outputs

Global-scale DAYCENT simulations can be divided into 4 major steps: 1) acquisition and formatting of model input data required to run DAYCENT; 2) Conducting global simulations of native vegetation and historical cropping 3) conducting global simulations of baseline modern cropping and GHG mitigation options, and 4) post processing and compilation of model results. Baseline modern cropping is intended to represent typical cropping practices, i.e., conventional till cultivation and a single application of N fertilizer before planting without nitrification inhibitors. The resolution of the simulations is determined by the resolution of available model driver data and of data needed for processing model outputs. The resolution for these simulations was 1.9° x 1.9° latitude/longitude cells because this was the resolution of the only global daily weather data that the authors were aware was available. Cropping practices (fertilization rates, nominal planting dates) were assumed to be uniform within countries or regions.

2.2.1 DAYCENT inputs

The data for different inputs required to run DAYCENT was available at various resolutions so some data sets had to be aggregated wile others were disaggregated. The resolution of the weather data (1.9 X 1.9°) dictates the resolution of the simulations. Consequently, soils data, available at the 0.5° scale, were aggregated while country level N fertilizer application rates were assumed to apply to all the 1.9° cells simulated in each country. The following paragraphs describe model inputs in detail.

Daily maximum/minimum temperature and precipitation were acquired from NCEP (National Centers for Environmental Prediction http://www.cdc.noaa.gov/cdc/data.ncep. reanalysis.html). NCEP data is available for the globe at 1.9° resolution from 1948 to present but we used weather data for 1991-2000 so that any long term changes in weather patterns would not affect our results.

Soil texture class and native vegetation data required by DAYCENT were derived from the Potsdam model comparison exercise (Cramer at al., 1999). The Potsdam data set was gridded at the 0.5° scale. For each 1.9° NCEP cell the modal vegetation class was identified by overlaying the NCEP grid on the Potsdam grid. Soil texture class data for each 1.9° was derived in a similar manner. Soil hydraulic properties needed for model inputs were calculated from model Potsdam surface texture class and Saxton et al.'s (1986) hydraulic properties calculator. The Potsdam soil texture data was derived from FAO (1996) and the native vegetation class from Melillo et al. (1993).

Global data on agricultural management events such as annual fertilizer and manure application rates, and planting dates were based on the data presented in a recent paper on global crop yield modelling with DAYCENT (Stehfest et al, in review).

The amount of fertilizer applied for modern cropping per country and crop had been derived from the international fertilizer Industry Association (IFA, www.fertilizer.org), which provides this information for the important crop-producing countries and their main crops. The database contains percent of area fertilized and application rate, which was multiplied to get average application rates. That is, for the simulations we assumed that 100% of cropped land was fertilized. For country/crop combinations where no IFA data were available it was assumed that the synthetic fertilizer input equals the N removed though yield based on FAO yield data minus the applied manure N.

Manure application per country was derived from Siebert (2005). Based on 12 IMAGE animal types and their specific N excrement rates the annual manure productions were estimated and equally distributed within the agricultural land within countries (Stehfest et al., in review).

Little data exist at the global scale for planting and cultivating dates because these vary based on local weather conditions and other factors. Therefore simulated global planting dates as presented in Stehfest et al., (in review) were used. They had been derived on a 30 min grid, using a climatic envelope and an optimization procedure. This optimization procedure applied a simplified DAYCENT routine to simulate potential yields for planting dates at the first day of each month of a year and then the planting month that led to the highest yield was selected as the nominal planting date. For the Daycent simulations presented here, country averages of planting dates were calculated from the 0.5 min maps.

In DAYCENT, germination occurs on the nominal planting date if the 7 day running average soil temperature in the 2-5cm layer is sufficiently warm. If not, germination will occur on a later date when the 7 day running average soil temperature exceeds the plant specific minimum soil temperature required for germination. Harvest date was controlled by accumulated growing degree-days since germination and 75% of above ground residue was assumed to be removed during harvest, along with 100% of grain. Conventional tillage was implemented before the nominal planting date and all crops were grown continuously in stead of in rotation with other crops.

Application dates of synthetic fertilizer and manure are also highly variable and little information is available at the global scale. As these are mainly linked to planting dates and crop growth stages we applied the following rules to define the application events: Manure was applied 2 weeks before and synthetic fertilizer 2 days before the nominal planting date.

Three global vegetation maps were used to identify crop areas in each global 1.9^{o} cell, GLC 2000 (http://www-gvm.jrc.it/glc2000/), SAGE (http://www.sage.wisc.edu/index.html; Ramankutty and Foley 1998) and EROS (http://edcsns17.cr.usgs.gov/glcc/). The maps were combined to maximize the potential cropping area. Cells with less than 5% cropped area were not simulated. Crop area was assumed to have peaked globally during the 1990's, and peak crop area from this time was used throughout the simulations. Global crop area was validated by comparing estimated crop area to reported country-level crop area from the FAO for the year 2000. Comparisons showed greater than 90% agreement for the crops simulated.

2.2.2 Simulations of native vegetation and 20th century cropping

Two sets of simulations were performed for each global cell that was covered with at least 5% cropped land: one for the native vegetation (year 1 to 1899) and one to represent 20^{th} century agricultural practices (1900 to 1990). Simulation of 1900 years of native vegetation was needed to ensure that soil organic matter (SOM) pools in the model were at steady state and to provide native baseline GHG fluxes to compare with those from agriculture. Although land in many parts of the globe has been cropped since before 1900, we made the simplifying assumption that cropping did not start until 1900. Simulations of plow-out and 20^{th} century cropping were needed to establish modern day SOM levels. This is important because present day SOM levels influence the extent to which soils can lose or gain carbon in the future. SOM levels also influence N_2O emissions. These simulations assumed conventional tillage cultivation, gradual increases in synthetic fertilizer application until 1990, and region specific crop cultivars. Synthetic fertilizer was not added before 1951 and we assumed that this amount was initially small and gradually increased to present-day levels in 1990. The 10 year NCEP weather file was recycled to drive simulations for each cell.

2.2.3 Simulations of baseline modern cropping and mitigation options

Values for state variables in the model (e.g., SOC, mineral N) from the year 1990 were saved and used as initial conditions for the simulations representing baseline modern cropping and the mitigation options considered. Baseline modern cropping, reduced fertilizer, precision fertilizer application, use of nitrification inhibitors, and no-till cultivation were simulated in each cell from 1991-2020. For the years 2001-2020, fertilizer rates were assumed to be a function of projected yield estimates. Linear equations for each crop were derived by regressing country level fertilizer rate estimates with yield estimates. 70% of baseline N fertilizer rates were also simulated. Precision fertilizer application is defined as adding fertilizer in 3 applications, each equal to 1/3 the nominal amount, instead of all at once just before planting as is the case with the baseline scenario. The first application was 2 days before the nominal planting date and the 2^{nd} and 3^{rd} were 16 and 47 days after the nominal planting date. Nitrification inhibitors were implemented in the model by reducing calculated nitrification rates by 50% for 2 months after the inhibitor is applied based on data from Bronson et al. (1992). The no-till option consists simply of removing the annual plow event from the baseline simulations. We also simulated the interaction of no-till and nitrification inhibitors combined. As with the native and historical simulations described above, each cell specific 10 year NCEP weather file was recycled to drive the baseline modern cropping and mitigation simulations.

2.2.4 Post processing and compilation of model outputs and calculation of net GHG flux

To isolate the anthropogenic portion of direct and indirect N_2O emissions, simulated direct N_2O emissions and indirect emissions from N volatilization and NO_3 leaching from the native condition were subtracted from these N loss vectors for modern cropping. This was done for the baseline and for each of the mitigation scenarios for each crop in each cell for each year. Indirect N_2O emissions were calculated by multiplying DAYCENT outputs for N gas volatilization and NO_3 leaching by the default IPCC (1997) factors of 0.01 and 0.025, respectively. That is, IPCC (1997) methodology assumes that 1% of non-N_2O N gas volatilized from soils will be re-deposited and converted to N_2O and 2.5% of NO_3 leached into waterways will be denitrified and emitted to the atmosphere as N_2O. Direct and indirect N_2O emissions were converted to CO_2-C equivalents by accounting for molecular stoichiometry and assuming that the global warming potential of N_2O is 310 on a mass basis. Decadal mean anthropogenic emissions were calculated centered around the years 2000, 2010, and 2020. The relative differences between emissions from the baseline and each of the mitigation options were calculated to facilitate comparisons of the different scenarios. Net GHG flux was calculated by accounting for changes in SOC, the CO_2-C equivalents of N_2O emissions, and the CO_2 associated with the production of synthetic N fertilizer (assuming 0.8 g CO_2-C is emitted for each g N produced). Global N_2O emissions estimated using DAYCENT were compared with estimates using IPCC (1997, 2006) methodologies for quality control.

3. Results and discussion

N_2O is typically the major greenhouse gas emitted from non-rice cropping. To ensure that estimated emissions were reasonable, DAYCENT (baseline option) simulated average annual (1991-2000) N_2O emissions for maize, wheat and soybean crops were compared with emissions estimated using IPCC (1997; 2006) methodologies. IPCC (1997) methodology estimated higher direct emissions, particularly for soybean, DAYCENT estimated higher indirect emissions, particularly for soybean, and total emissions were ~8% lower using DAYCENT (Table 1). This is consistent with USA national scale simulations which showed that the major discrepancy between DAYCENT and IPCC (1997) estimates was with N-fixing crops such that DAYCENT estimated much higher indirect emissions from these crop types, particularly from NO_3 leaching, while IPCC methodology estimated much higher direct emissions for N fixers (Del Grosso et al., 2005). However, when using IPCC (2006) methodology, the agreement with DAYCENT is much better (Table 1). There are 4 major changes in IPCC (2006) compared to IPCC (1997) methodology for N_2O emissions from soils. First, the emission factor for direct soil emissions was lowered from 1.25 to 1.0% of N inputs. Second, N fixed by legumes in above ground biomass is no longer considered to be an N input to soil, although N in residue of legumes is still considered an N input. Third, N from crop residue is now considered eligible for NO_3 leaching/runoff. Lastly, the emission factor for indirect emissions associated with NO_3 leaching/runoff was lowered from 2.5 to 0.75%. These changes result in much closer agreement with DAYCENT for soybeans and lower overall emissions (Table 1). However, we emphasize that in any given cell in any given year, N_2O estimated using DAYCENT and IPCC (2006) methodologies can differ substantially, but after averaging through time and aggregating to the global scale, the methodologies show remarkably close agreement (less than 1.5% difference in this case) for total N_2O emissions from the 3 crops simulated. This increases confidence in model results because the IPCC (2006) methodology is based on N_2O emission and N input data from a large (846 measurements) global data set (Bouwman et al, 2002) so DAYCENT should show close agreement at large scales.

Simulated N_2O emission rates are largely driven by N additions but are also influenced by climate and soil texture (Figure 1a). Emissions are high in parts of western Europe, Asia, and North America where fertilizer addition rates tend to be high (Figure 1b). However, high fertilization rates do not necessarily lead to high N_2O emissions. For example, emissions are moderate in the southeast USA where soils tend to be coarse textured but high in southeast China where soils are finer textured. Another reason for high emissions in China is manure amendment rates tend to be high compared to the USA. NO_3 leaching is also strongly influenced by soil texture such that leaching is lower in southeast China than in the southeast USA (Figure 1c). Although high leaching rates are typically associated with areas of high rainfall, the model shows significant leaching in some dry areas, such as central Australia. In DAYCENT, once NO_3 is carried below the rooting zone and into the subsoil it is considered to be leached. Thus, high leaching in dry areas indicates rainfall events of sufficient magnitude occasionally occur to leach NO_3 below the rooting zone but it should not be inferred that the NO_3 is necessarily leached into aquatic systems. Data showing high levels (>1000 kg N ha^{-1}) of NO_3 accumulation in the subsoil of arid soils in the western USA support this model behavior (Walvoord et al., 2003).

Figure 1 shows N fluxes per unit area of cropped land for the 3 crops simulated but contains no information regarding the amount of land that is cropped in different regions. To address this, we calculated national or regional totals for N fluxes. The USA and former Soviet Union used the most fertilizer and had the highest absolute N losses (Table 2). The seven nations or geographical areas shown in Table 2 were responsible for over 80% of agricultural N fertilizer inputs, N inputs from fixation, NO_3 leaching, and 77% of N_2O emissions for the crops simulated.

N_2O emissions make up the largest portion of net GHG flux for all management scenarios considered (Figure 2a). Reducing fertilizer to 70% of the base application led to the largest decrease in N_2O emissions while split N fertilizer application led to the smallest reduction. SOC was assumed to be at steady state under the baseline, and increased with all mitigation options considered except fertilizer reduction. Grain yields increased relative to the base with the split fertilizer and nitrification inhibitor options, was close to neutral for no-till, and decreased with reduced fertilizer (Figure 2b). The decrease in grain yields with the lower fertilizer corresponds to lower crop residue inputs and hence decreased SOC for this option (Figure 2a).

At the global scale, all of the options considered, except reduced fertilizer, resulted in decreased net GHG flux and the combination of no-till and nitrification inhibitors led to the largest reduction. Decreased SOC under the reduced fertilizer option more than compensates for smaller N_2O emissions which results in higher net emissions relative to the base. One caveat of this analysis is that mitigation of N_2O emissions is more permanent whereas changes in CO_2 emissions are transient. That is, the net GHG benefits of C storage with the no-till and other options that increased SOC and the decrease in soil C with reduced fertilizer are expected to gradually diminish overtime as SOC levels approach a new steady state commensurate with the respective management practices. Although N_2O emissions are sensitive to SOC levels, management factors that influence N_2O emissions more directly (e.g., nitrification inhibitors) are expected to have a larger impact on emissions than changes in SOC levels. We caution that our net GHG flux equation does not account for all the GHG sources associated with agriculture, such as emissions from farm operations and manufacture of pesticides.

Although all the mitigation options considered, except reduced fertilizer, led to reduced net GHG flux at the global scale, some regions showed counter-intuitive results. For example, no-till cultivation led to increased net GHG flux in some wet environments because no-till conserved soil water and helped maintain the anaerobic conditions that facilitate denitrification. Also, in some colder regions, use of no-till leads to little, if any, increase in SOC because the residue layer on the surface insulates the soil so soil temperatures do not warm as quickly in Spring. Consequently, the growing season is shortened, plant growth is reduced, and the residue inputs that supply the SOC pool are reduced. For these reasons, particular mitigation strategies should not be recommended universally and local conditions should be considered when identifying best management practices.

4. Conclusions

DAYCENT model results suggest that there is significant potential to reduce GHG emissions from cropped soils and to increase yields. Precision application of fertilizer and nitrification inhibitors allow for more N uptake by plants and reduce gaseous N losses and NO_3 leaching. No-till cultivation, which facilitates C sequestration in soils, combined with nitrification inhibitors provided the maximum reduction in GHG fluxes among the scenarios considered. However, these results are limited for several reasons. First, the scale of the weather and soil driver data (~1.9°) is very coarse. This means that for these simulations weather and soil class did not very within each ~1.9° latitude/longitude cell. The scale for land management was even greater; cropping practices in terms of N amendment rates and nominal planting dates were designated at the national level. We did not account for the fossil fuel use associated with manufacture of nitrification inhibitors or applying N fertilizer in 3 doses instead of all at once. Lastly, we assumed that all crops were grown in monoculture and did not account for multi-crop rotations. For these reasons, the model projections presented here should be viewed as hypotheses which should be compared with data and other modeling exercises. Even so, this is a valuable endeavor because few global scale analyses of GHG fluxes from cropped soils using process based models have been previously reported. We also argue that even though the simulations were conducted at an extremely coarse resolution and many simplifying assumptions were made, this is still likely to be an improvement compared to IPCC methodology which estimates N_2O emissions based solely on N inputs and does not account for weather and soil class at all. Also, IPCC methodology can not be used to evaluate mitigation options except for those that involve reducing N fertilizer inputs.

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Table 1. Global scale mean annual (1991-2000) anthropogenic N_2O emissions (Tg CO_2 equivalents) calculated using IPCC (1997; 2006) methodologies and the DAYCENT ecosystem model for 3 major crops. See text for summary of the changes in IPCC methodology.

	N_2O direct		N_2O indirect		total N_2O		% delta total N_2O
	IPCC	DAYCENT	IPCC	DAYCENT	IPCC	DAYCENT	(DAYCENT-IPCC)/IPCC
IPCC (1997) Methodology							
corn	183	118	110	115	293	233	-20.6
wheat	284	274	171	225	454	500	10.0
soybean	119	38	8	36	127	73	-42.1
sum	586	430	289	377	875	806	-7.8
IPCC (2006) Methodology							
corn	146	118	48	37	195	154	-20.7
wheat	227	274	75	71	302	345	14.5
soybean	36	38	9	12	46	50	8.8
sum	410	430	132	120	542	549	1.4

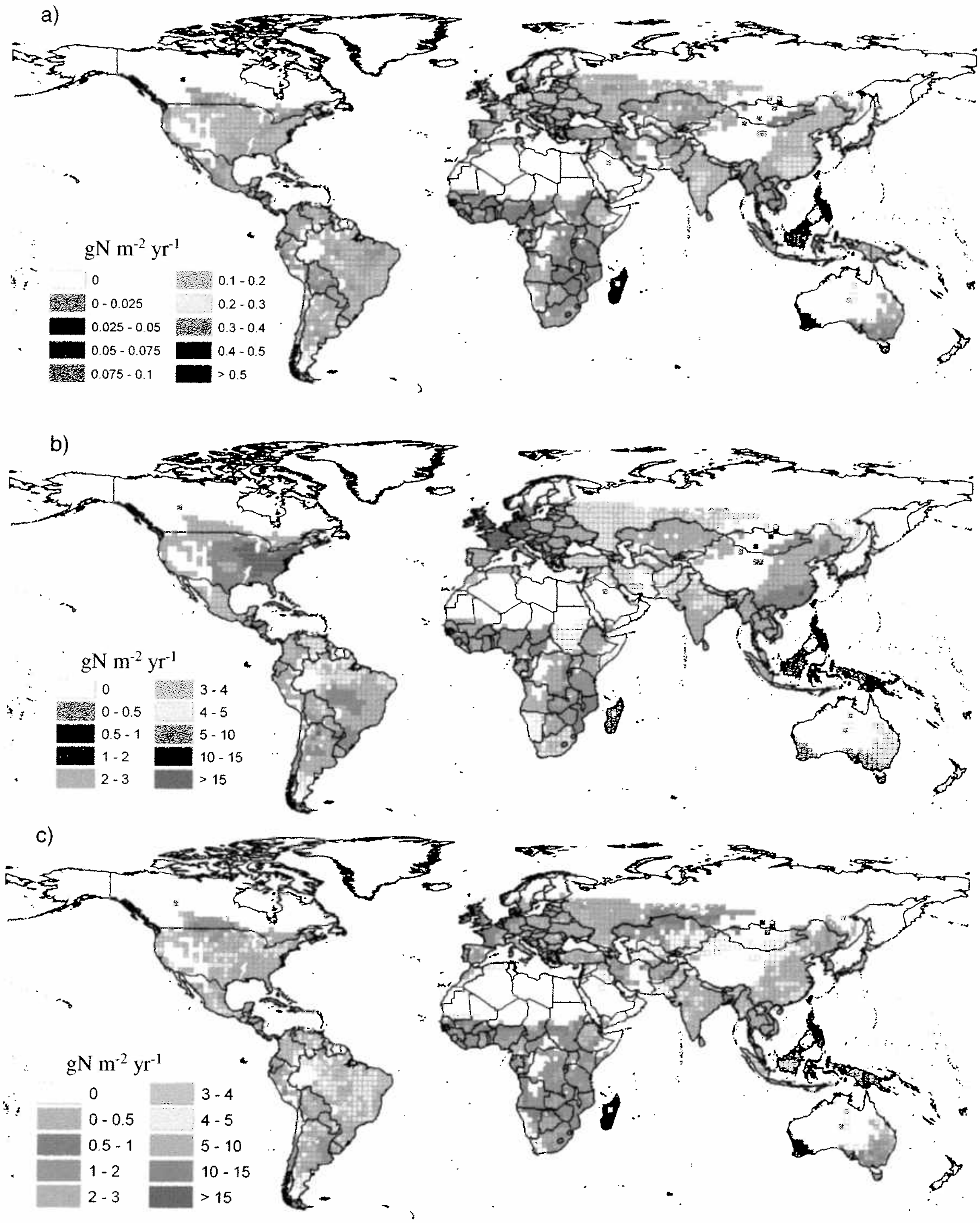
Table 2. Global/regional scale mean annual (1991-2000) N inputs and losses for corn, wheat and soybean in units of Gg N yr^{-1}.

Region	N fertilizer	N fixed	N_2O	NO_3 leached
Globe	54.4	9.53	1.15	32.2
USA	16.5	5.54	0.22	7.7
Former USSR	9.6	0.03	0.24	5.5
China	6.3	0.65	0.12	3.0
Western Europe	6.3	0.02	0.11	3.8
Eastern Europe	2.7	0.02	0.05	1.8
Brazil	0.8	1.77	0.04	1.2
India	2.0	0.30	0.10	3.0

Figure captions

Fig. 1. 10 year crop area weighted mean annual (1991-2000) N_2O emissions (a), N inputs from fertilizer additions and fixation (b), and NO_3 leaching (c) simulated by DAYCENT for corn, wheat, and soybean.

Fig. 2. 10 year mean annual (2011-2020) global GHG fluxes simulated by DAYCENT for cropping of corn, wheat and soybean for baseline management and the mitigation options considered (a) and relative differences for the mitigation options compared to the baseline for grain yields and GHG fluxes (b).



a)
gN m-2 yr-1
0
0 - 0.025
0.025 - 0.05
0.05 - 0.075
0.075 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
> 0.5
b)
gN m-2 yr-1
0
0 - 0.5
0.5 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 10
10 - 15
> 15
c)
gN m-2 yr-1
0
0 - 0.5
0.5 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 10
10 - 15
> 15

Fig. 1

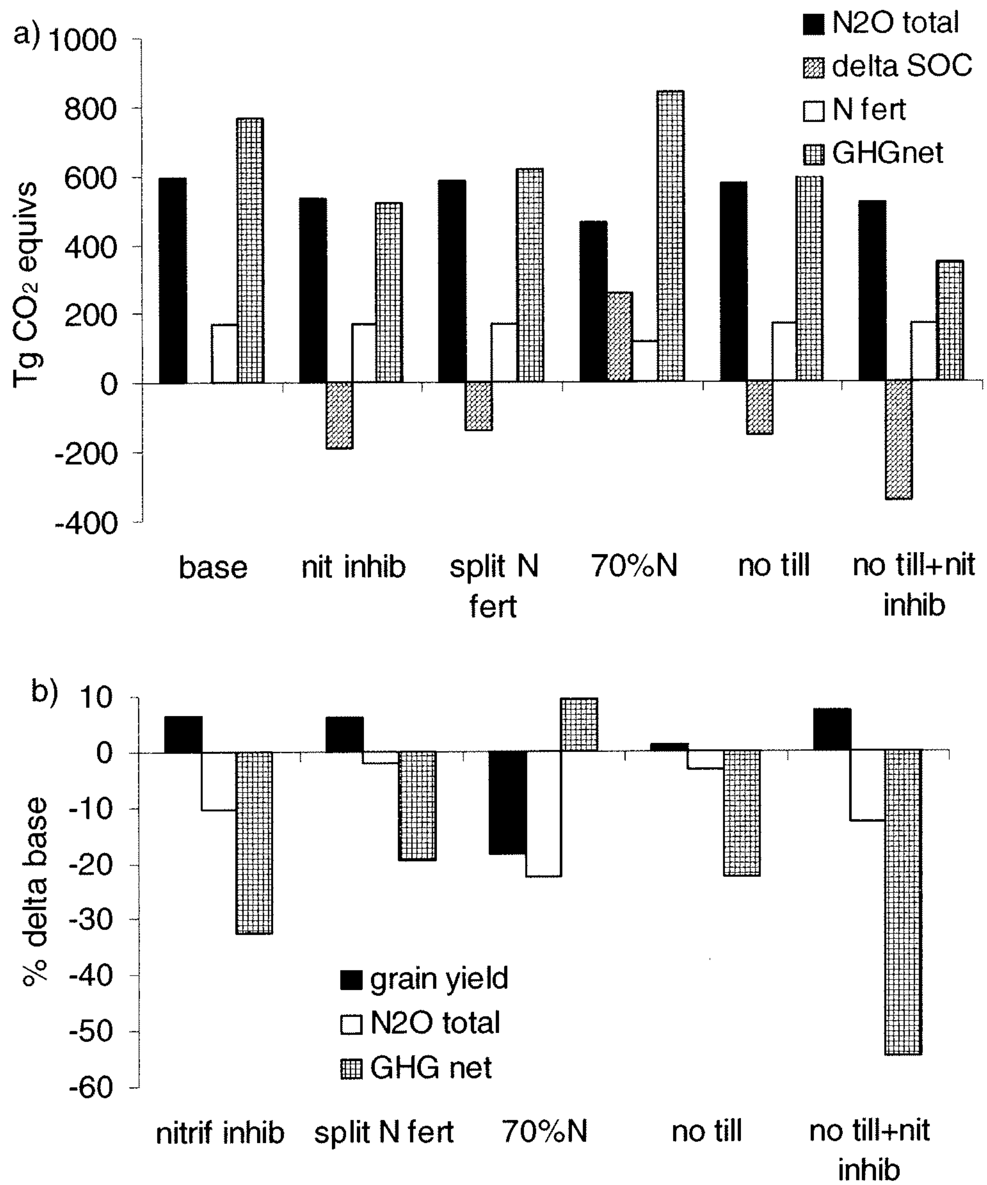

a)
b)
N2O total
delta SOC
N fert
GHGnet
Tg CO2 equivs
1000
800
600
400
200
0
-200
-400
base
nit inhib
split N fert
70%N
no till
no till+nit inhib
10
0
-10
-20
-30
-40
-50
-60
% delta base
grain yield
N2O total
GHG net
nitrif inhib
split N fert
70%N
no till
no till+nit inhib

Fig. 2