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Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils ☆

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A B S T R A C T

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 $1.9° \times 1.9°$ 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%.

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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 (GHGs) 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 and Ehhalt, 1977; Crutzen, 1981) 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,

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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 (Sherrod et al., 2003; Lal, 2004).

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 GHGs (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. (2007).

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 (Parton et al., 1998; Del Grosso et al., 2001a). 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.