Nutrient Cycling in Agroecosystems **60:** 159–175, 2001.

Comparing a process-based agro-ecosystem model to the IPCC methodology for developing a national inventory of N_2O emissions from arable lands in China

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Key words: assessment, China, cropland, IPCC, modeling, Nitrous oxide, N_2O

Abstract

Nations are now obligated to assess their greenhouse gas emissions under the protocols of Article 4 of the United Nations Framework Convention on Climate Change. The IPCC has developed 'spreadsheet-format' methodologies for countries to estimate national greenhouse gas emissions by economic sector. Each activity has a magnitude and emission rate and their product is summed over all included activities to generate a national total (IPCC, 1997). For N_2O emissions from cropland soils, field studies have shown that there are important factors that influence N_2O emissions at specific field sites that are not considered in the IPCC methodology. We used DNDC, a process-oriented agroecosystem model, to develop an *unofficial* national inventory of direct N_2O emissions from cropland in China. We assembled county-scale data on soil properties, daily weather, crop areas, N-fertilizer use, livestock populations (for manure inputs to cropland), and agricultural management for the 2500 counties in mainland China. Total 1990 cropland area was 0.95 million km^2. Total N-fertilizer use in China in 1990 was 16.6 Tg N. The average fertilization rate was 175 kg N ha^{-1} cropland. One-year simulations with DNDC were run for each crop type in each county to generate estimates of direct N_2O emissions from soils. National totals were the sum of results for all crop simulations across all counties. Baseline simulations estimated that total N_2O emission from arable land in China in 1990 was 0.31 Tg N_2O-N yr^{-1}. We also ran simulations with zero N-fertilizer input; the difference between the zero-fertilizer and the baseline run is an estimate of fertilizer-induced N_2O emissions. The fertilizer-induced emission was 0.13 Tg N_2O-N yr^{-1}, about 0.8% of total N-fertilizer use (lower than the mean but within the IPCC range of 1.25±1.0%). We compared these results to our estimates of county-scale IPCC methodology emissions. Total emissions were similar but geographical patterns were quite different.

Introduction

Article 4 of the United Nations Framework Convention on Climate Change states that 'All Parties ... shall ... develop, periodically update, [and] publish ... national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies ...' In response to this mandate, the Intergovernmental Panel on Climate Change (IPCC) has coordinated groups of experts to develop and periodically update national inventory methodologies for various greenhouse gases. These methodologies are generally developed separately by greenhouse gas and economic sector, e.g., N_2O emissions from agriculture. In order to meet the requirement of being applicable by all nations the methodologies must be developed such that nations will have or can generate the data necessary to apply the methodology to develop a national inventory. This has led to assessment methodologies that are in a 'spreadsheet' format. In these methodologies, each activity (e.g., synthetic nitrogen fertilizer use) has a magnitude (e.g., tonnes of N applied per year) and an emission rate (e.g., 1.25%

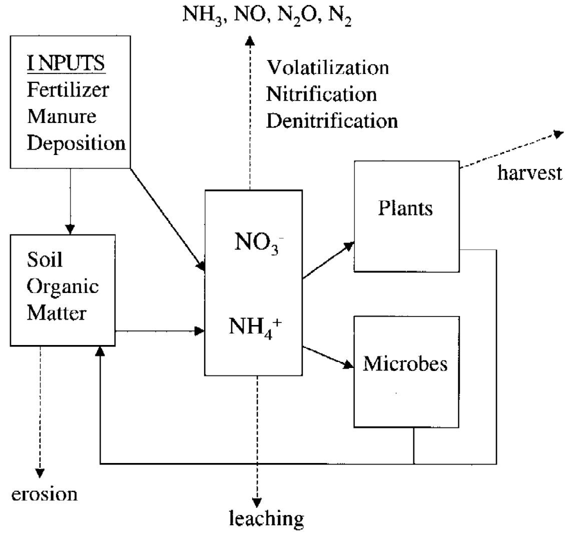

Figure 1. A schematic representation of the nitrogen cycle in agro-ecosystems as captured in DNDC and other process-based simulation models. Note that the IPCC methodology only considers nitrogen inputs, ammonium volatilization losses, and nitrogen returned to the field as crop residue.

lost as N_2O in direct emission to the atmosphere from the cropland soil) and the product of these is summed over all included activities to generate a national total (IPCC, 1997). In this paper we compare and contrast two methods for developing national inventories for direct N_2O emissions from agricultural soils: a process-oriented ecosystem model and the empirical IPCC methodology.

Assessing N_2O emissions from agriculture

Nitrogen cycling in agro-ecosystems

Nitrogen cycles actively through plants, soil, water, and air in agro-ecosystems (Figure 1). Vigorous plant growth requires the availability of adequate mineral nitrogen (ammonium and nitrate) in the plant root zone. This available nitrogen comes from both internal cycling and external inputs. Nitrogen mineralization during decomposition of soil organic matter generates ammonium, and microbially-mediated nitrification converts this to nitrate. Fertilization (synthetic nitrogen fertilizers, farmyard manure, green manure), nitrogen fixation, and atmospheric deposition comprise the external nitrogen inputs. Losses from the ecosystem are by leaching and runoff of dissolved nitrogen, erosional loss, gaseous losses from ammonia volatilization and both nitrification and denitrification, and removal of nitrogen in plant tissues at harvest. Through N-immobilization, soil microbes compete with the plants for available nitrogen in the soil. Gaseous N_2O is generated as an intermediate product in microbially-mediated N-transformations in the soil (nitrification and denitrification). The flux of N_2O from the agricultural soil to the atmosphere depends on the rates and interactions of all of these processes.

There are two general approaches to estimating direct N_2O flux from soils in agro-ecosystems. In a strict empirical model, N_2O flux is proportional to some easily quantifiable factor, and the details of the nitrogen cycle in Figure 1 are ignored. For example, Xing (1998) estimates N_2O emissions from croplands in China by using fixed annual emission rates for each crop/management system (e.g., double rice), based on field data from an example of most of these systems in China. To generate emission estimates for a region, these emission rates are multiplied by the cropland area in each management system. The IPCC methodology (discussed below) is also a strictly empirical model. Process-oriented ecosystem models attempt to simulate many or all of the components of the nitrogen cycle shown in Figure 1. As a result, process-oriented models require many more details about the ecosystem being simulated than the strict empirical models. Of course, at the fundamental level the processes in a process-oriented model are represented by functions based on either experimental data or basic physical and chemical laws. In this way, a process-oriented model can be driven by temperature, moisture, pH, redox potential, and other basic environmental factors what are not usually applied to strictly empirical models.

The current IPCC methodology for N_2O emissions from agriculture

The first phase of IPCC methodology development was published in 1995 (IPCC, 1995). This methodology used a strict empirical model to calculate N_2O emissions occurring directly from the soil in arable lands, considering N sources from synthetic fertilizers, organic N from animal manure and crop residues returned to the field, and biological N fixation associated with leguminous crops (Mosier et al., 1998). The methodology equated direct N_2O emissions to 1.25 ± 1.0% of applied N, following Cole et al. (1996). This fractional loss as N_2O of nitrogen amendments was based on a review of field data and covers 90% of the range of this published field data (Bouwman, 1994, 1996; Mosier et al., 1998). Most of these data came from field studies in temperate agroecosystems in North America and Europe.

The current IPCC PHASE II methodology for generating national N_2O inventories from agriculture (IPCC, 1997; Mosier et al., 1998) extends the earlier methodology by including both direct N_2O emissions from animal production (including waste management), and indirect agricultural N_2O emissions. These indirect emissions are primarily from denitrification of N leaving arable land via leaching and runoff, but also of N in sewage generated from consumption of agricultural products, and N volatilized from arable soils and subsequently re-deposited on terrestrial ecosystems (Mosier et al., 1998). The PHASE II methodology maintains the recommendation of a fixed N_2O release rate of 1.25 ± 1.0% for N applied as fertilizer, manure, green manure, or N fixed by leguminous crops. Additional direct N_2O emissions are attributed to cultivation of organic soils (5 kg N ha^{-1} yr^{-1} in temperate zones and 10 kg N ha^{-1} yr^{-1} in the tropics).

The IPCC methodology requires national statistics on fertilizer use, livestock populations, and crop residue management. It does not require data on cropland areas, soils, climate/weather, fertilizer types, or other details of agricultural management (e.g., tillage, irrigation). The required data do not need to be georeferenced in a sub-national scale GIS database. As a result, the IPCC methodologies do not account for regional differences in agro-ecosystem characteristics. There can be important differences across the country in the interactions between climate, soil properties, crop type, fertilizer use, and agricultural management that can lead to highly irregular N_2O emission patterns at the national scale, particularly for large agricultural nations (e.g. Li et al., 1996).

Process modeling of N_2O emissions from arable land

A number of 'process-oriented' simulation models have been developed over the last several years with the objective of simulating terrestrial ecosystem carbon and nitrogen biogeochemistry and nitrogen trace gas emissions (e.g., Li et al., 1992a, Engel and Priesack, 1993; Grant et al., 1993, Parton et al., 1996; Potter et al., 1996). In the analysis below, we used the DNDC model to generate estimates of direct N_2O emissions from agricultural soils for each county in China. The DNDC model is a detailed synthesis of

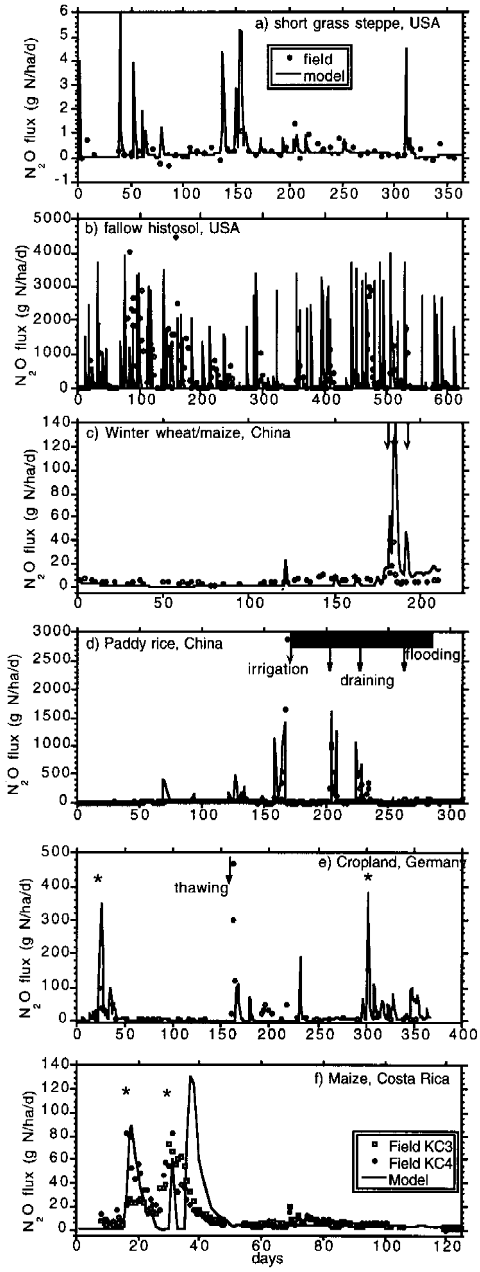

Figure 2. Comparison of measured N_2O emissions and DNDC simulations for six sites. (a) Short grass steppe in eastern Colorado USA (Mosier et al., 1996). Day 1 is 1 Jan 1991. (b) Fallow organic soil in southern Florida, USA (Terry et al., 1981). Day 1 is 16 April 1979. (c) Fertilized winter wheat/maize rotation near Beijing, China (Zhuang et al., unpublished data). Arrows indicate timing of irrigation or heavy rainfall. Day 1 is 20 Oct 1997. (d) Paddy rice field in Jiangsu Province, China (Zheng et al., 1999). Closed arrow marks timing of irrigation and flooding period (shaded box). Open arrows mark timing of intermittent draining. Day 1 is 1 Jan 1997. (e) Fertilized cropland in Germany (Flessa et al., 1995). Asterisks mark timing of fertilizations; arrow marks timing of mid-winter thaw. Day 1 is 8 Aug. 1992. (f) Fertilized maize in eastern Costa Rica (Crill et al., 2000). Asterisks mark timing of fertilizations. Day 1 is 10 Nov. 1994.

processes controlling C and N cycling in soils (Li et al., 1992a,b; Li et al., 1994). It was developed to predict soil N_2O fluxes produced by nitrification and denitrification, and soil CO_2 fluxes produced by decomposition and root respiration. The model also simulates the dynamic behavior of a variety of C and N pools in the soil. The DNDC model has four primary sub-models. A soil climate sub-model uses daily meteorological data to predict soil temperature and moisture profiles, soil water flow and soil water uptake by plants for every hour of the simulation. A crop/vegetation growth sub-model simulates the growth of various crops from planting to harvest, predicting biomass and N-content of grain, stalk, and root. Crop growth is limited by nitrogen and water availability in the root zone. Transpiration water losses are calculated from crop growth and a crop-specific water-use-efficiency parameter. A decomposition sub-model has four soil carbon pools–litter, labile humus, passive humus, and microbial biomass. Each pool has a fixed decomposition rate and a fixed C:N ratio. Decomposition rates are influenced by soil texture, soil temperature and moisture, and potentially by nitrogen limitations. Nitrogen mineralized during decomposition enters the inorganic nitrogen pool as NH_4, where it accumulates, is nitrified to NO_3^- (with gaseous losses as NO and N_2O), or is removed via plant uptake, leaching, transformation to NH_3 and volatilization, or adsorption onto clay minerals. Soluble carbon levels, which fuel both nitrification and denitrification, are related to the fraction of carbon released by the decomposition of litter, labile humus, and dead microbial biomass that is re-assimilated in microbial biomass each day. The crop growth and decomposition sub-models operate on a daily time step. The hourly time-step denitrification sub-model in DNDC is activated by three conditions which increase soil moisture and/or decrease soil oxygen availability: rain events, flooding (as in irrigated rice agriculture), and freezing temperatures. This last denitrification trigger is a relatively new feature of DNDC. Air temperatures below $-5°C$ are assumed to freeze the soil and thus inhibit oxygen diffusion into the soil. An oxidation-reduction potential (Eh) is calculated depending on soil organic matter content as a proxy for oxygen consumption, and an Eh multiplier for the denitrification rate is computed. The version of DNDC used in this study did not simulate soil freeze/thaw and the associated impact on soil water content. For any initiation of denitrification the initial status of the available NO_3^- and soluble carbon pools is provided by the decomposition sub-model. The rates for each step in the denitrification reduction sequence ($NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$) are a function of soluble C, soil temperature (or Eh for frozen soils), soil pH, N-substrate availability, and denitrifier biomass. As the soil dries following a rain, the denitrifying portion of each model layer decreases with soil water content. The denitrification sub-model predicts the consumption of nitrate, and generates soil fluxes of NO, N_2O and N_2.

The DNDC model has been tested against a number of field datasets worldwide (Li et al., 1992b; Li et al., 1994; Xu, 1997; Frolking et al., 1998; Plant, 1999; Weitz, 1999; Stange et al., 1999). Most of the tests showed that DNDC was able to capture general patterns and magnitudes of N_2O emissions observed in field, although discrepancies existed for some cases. We summarize six cases here, selected from the US, China, Germany and Costa Rica to cover a wide range of climate/soil/land cover/management conditions (Table 1). In multi-year, year-round observations, Mosier et al. (1996) measured very low N_2O flux rates (<2 g N/ha/day) from a grassland in Colorado, USA. By running with the local climatic, soil and land-cover conditions, DNDC repeated the low rates but with several relatively high pulses (2–6 g N/ha/day) associated with denitrification during either soil thawing or rainy weather (Figure 2a). In contrast, very high N_2O flux rates (up to 4600 g N/ha/day) were measured on an organic soil in Florida, USA (Terry et al., 1981). DNDC predicted high rates of nitrogen mineralization in the soil. Nitrate and ammonium rapidly accumulated in the soil between rainfall events, and rain stimulated high peaks of N_2O emission through denitrification due to high DOC and nitrate in the soil (Figure 2b). At a fertilized winter wheat/maize field in Changping County near Beijing, China, Zhuang and colleagues measured low N_2O emissions from October 1997 through June 1998, except after the consecutive irrigation and rainfall events in late April (YaHui Zhuang, pers. comm.). DNDC predicted water as a limiting factor for N_2O production in the soil, and captured the episodes of N_2O emissions following the irrigation/rainfall events in late April in 1998, although the magnitude of the predicted peaks was twice the field observations (Figure 2c). Zheng et al. (1999) measured N_2O fluxes from a paddy rice field in Jiangsu Province, China, and observed episodes of high N_2O emissions following the paddy draining during the growing season. DNDC generated episodic high N_2O emission rates, caused by sudden interruptions in the final step of denitrification (N_2O reduction to N_2) caused by the draining practices (Figure 2d). Flessa et al. (1995) observed N_2O pulses emitted from a fertilized cropland in Scheyern, Germany following fertilization or spring thawing (Flessa et al. 1995). DNDC captured the impact of fertilization on N_2O emissions, but underestimated the N_2O fluxes during thawing (Figure 2e). In a maize field in the lowland tropics of Costa Rica, Crill et al. (2000) measured high N_2O fluxes following fertilizer applications. DNDC indicated that available nitrogen was the major factor limiting N_2O production at the site, and captured the immediate impacts of fertilization on N_2O emissions although the pattern was somewhat different from observations (Figure 2f). Without any alteration in its internal parameters, DNDC generally repeated the patterns and magnitudes of N_2O emissions observed in the six field sites, which varied from 0.1–165 kg N/ha per year across various climate zones, soil types, land cover, and management. These results imply that DNDC may have incorporated many of the fundamental processes influencing directions and rates of the key biochemical and geochemical reactions controlling N_2O emissions from agricultural soils, and thus may be suitable for application to a wide range of agroecosystems.

A series of sensitivity tests (Li et al., in review) were conducted to explore which model inputs had the greatest and least effect on N_2O emissions. Simulations were conducted for sites in five states and five provinces, selected from the major agricultural areas in the US and China, ranging in latitude from 23° to 45°N. A baseline scenario was composed by including the local daily weather for 1990 and average values of soil clay fraction, pH and organic carbon content for each state or province, and a uniform management for all the tested areas. Sensitivities of N_2O emission to the climate and soil factors were tested by varying each of the factors in its typical range in the state or province, while holding other factors at their average values. In addition to the tests for each of the single factors, two extreme scenarios were constructed. Based on the single factor tests, we combined all the extreme values of the factors that caused a reduction in N_2O emissions to form an extreme negative scenario, and the same for an extreme positive scenario. The two extreme scenarios should bound the rare but possible combinations of the climate and soil factors which could generate very high or low N_2O emissions. The sensitivity tests showed that soil organic carbon content (SOC) was the most sensitive factor for N_2O emissions (see also Li et al., 1996). Running the model twice, once with the maximum SOC and once with the minimum SOC for each specific area, generated a range of N_2O emissions which was broad enough to cover the variations caused by varying other climate or soil factors in the area. These ranges accounted for more than 80% of the extreme N_2O emission variability for most sites. We thus chose to use the maximum and minimum SOC values reported for a county to produce a range of N_2O emissions for each simulation case in our analysis. We believe that this range should be broad enough to cover most variability in N_2O flux that would be caused by variations in other climate or soil factors. In the next section we report the mean emissions (average of high and low simulations for each crop in each county); the emissions ranges are presented in an uncertainty discussion in Section 4.

N_2O emission assessments for China

Input data sets

A major challenge in applying an ecosystem model at the national scale is assembling adequate data sets needed to initialize and drive the model. Applying the DNDC model to estimate N_2O emissions from arable soils in mainland China (Figure 3) required spatial databases of soil properties, daily weather, cropping and other agricultural management practices (Table 2). We developed county-scale data sets representing the status of agriculture in 1990 from maps, agricultural census data, and on-line databases. County-level agricultural census data and typical agricultural management practices for China in 1990 were prepared from three sources: (1) the Eco-Environmental Database (unpublished) of the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, (2) Chinese agronomy books (CRTSA, 1995; Huang et al., 1997), and (3) consultation with the Chinese Academy of Agricultural Sciences (Prof. Qingmu Chen, personal communication). The database contains county statistics on crop acreage for major crops, acreage of total cropland, sown area, grassland area, irrigated upland cropland area, nitrogen fertilizer use, and livestock and human populations. These data are available for 2483 counties in China (excluding Taiwan, Hongkong, Macao, and the numerous small islands in the South China Sea – Xisha Qundao, Nansha Qundao, Zhongsha Qundao). The database has been used previously for an analysis

Table 1. Test cases for the DNDC model

Site/Crop	MAAT °C	Precipitation mm/y	SOC g C/g soil	Fert. N	N_2O obs.	N_2O sim.	Ref.*
				kg N/ha/yr			
Colorado/grass	8.8	378	0.010	0	0.10	0.12	1
Florida/fallow	22.8	1406	0.430	0	164.9	134.8	2
China/corn	13.3	374	0.019	275	1.72	1.69	3
China/corn	13.3	374	0.019	0	0.59	0.41	3
China/rice	17.2	897	0.023	381	23.25	21.28	4
Germany/barley	7.7	904	0.012	50	4.17	5.67	5
Costa Rica/corn	24.7	4382	0.050	181	3.98	4.12	6
Costa Rica/corn	24.7	4382	0.050	0	1.02	0.90	6

MAAT – mean annual air temperature; Fert. – applied fertilizer; obs. – observed; sim. – simulated. * 1. Mosier et al., 1996; 2. Terry et al., 1981; 3. Zhuang, unpublished data; 4. Zheng et al., 1999; 5. Flessa et al., 1995; 6. Crill et al. 2000.

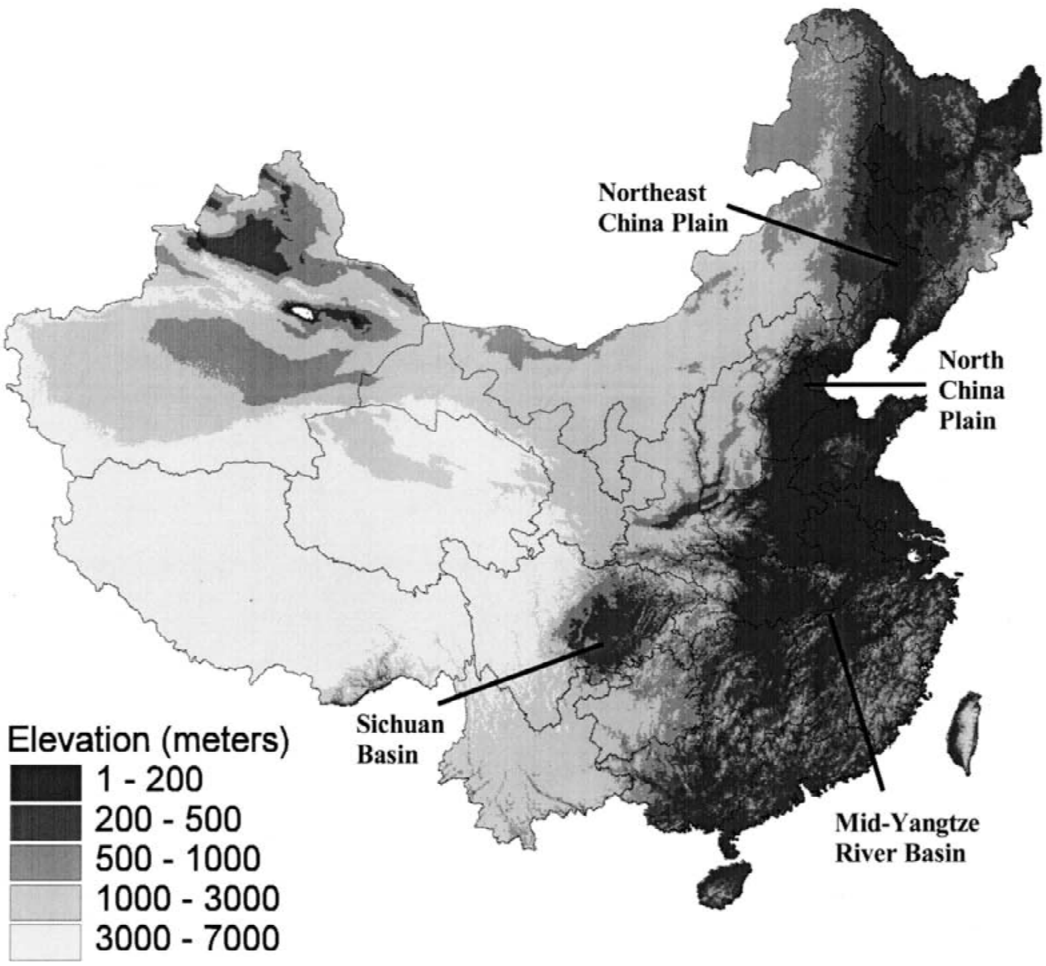

Figure 3. Relief map of China with provincial boundaries. Major agricultural regions are in the broad plains in Northeastern China, the North China Plain, the Sichuan Basin, the mid-Yangtze River basin, and along the southern coast. See also Figure 4.

of crop residue production in China (Zhuang et al., 1996), and in a comparison of crop area estimates from remote sensing landcover analysis (Frolking et al., 1999).

Harvesting two crops from a single plot in a single year (double cropping) is common in much of China. The cropland area data reflects the actual land area in crops, while the sown area data double counts land that is double cropped. Some counties report sown area as nearly double crop area (i.e. virtually all cropland is double cropped) and the total sown area for China in this database is 27% greater than the total cropland area. Major double cropping practices in China are rice/rice, maize/winter wheat, rice/winter wheat, and rice/rape oilseed (CRTSA, 1995; Huang et al., 1997). We estimated areas double cropped in each of these four categories based on the difference between total cropland and sown areas, and the area of rice, maize, winter wheat and rape for each county. For this estimation, we prioritized crops in this order: rice, maize, winter wheat, and rape. The calculated areas agree with the total cropland area, sown area, and each individual crop area (single plus double cropped), but the crop distribution into single and double crop totals may be not exactly consistent with the real situation. There is still some triple cropping in southern Guangdong and Hainan Provinces, which we treated as double cropping because we considered the area of triple cropping to be small at a national scale.

Maps of soil pH, soil texture, and soil organic matter content were digitized from 1:14 000 000 maps (ISS, 1986). These digitized maps were overlain on a 1:1 000 000 scale, county-level boundary map (CEISIN, 1998) representing China's national, provincial, regional and county administrative boundaries as of 31 December 1990 to determine the maximum and minimum value of each of these soil properties in each county. Daily weather data for 1990 needed to drive the model (precipitation and maximum and minimum air temperature) were acquired for 175 weather stations in China from the National Oceanic and Atmospheric Administration database (NOAA, 1994) and each county was assigned to the nearest weather station. N-deposition values were taken from the analysis of Holland et al. (1997).

Methods for Process-Model Simulations and Empirical Calculations

We developed two estimates of direct N_2O emissions from cropland soils in China based on these datasets. First, we used the DNDC model to simulate county scale N_2O emissions for each crop/management scenario in the county (e.g. winter wheat/maize rotation). An estimate of the likely range of N_2O emissions was generated for each crop by simulating one calendar year (1990) for each rotation in each county using both the high and low soil organic matter content values. County N_2O emissions (kg N_2O-N ha^{-1} yr^{-1}) were then calculated by multiplying the mean N_2O emission for each crop rotation scenario by the area of each crop rotation in each county, and summing over these totals for all crop rotations in a county. County totals were then summed to get a national total. Developing the national total was computationally-intensive, requiring about 4 days of computing time on a 350 MHz PC to calculate approximately 30,000 different annual scenarios. To explore the consequences of different management and climate scenarios, ten additional sets of the 30,000 annual simulations were run. Results from three of these alternative scenarios will be discussed below. A set of simulations was run with zero synthetic N fertilizer additions (all other factors unchanged) to estimate the 'fertilizer-induced' N_2O emissions as the difference between the baseline run and the 'zero-fertilizer' run. Similarly, a 'zero-manure' set of simulations was used to estimate 'manure-induced' N_2O emissions as the difference between the baseline emissions and the zero-manure emissions. A third scenario was explored, the impact of warmer temperatures by raising each day's maximum and minimum temperatures by +2 °C.

We also developed an approximate IPCC inventory, based on our database. This calculation was done at the county-scale and compared to the DNDC results both as an aggregated national total and as a county-scale pattern. The IPCC methodology (IPCC, 1997) estimates direct emissions of N_2O from croplands as

$$N_2O_{IPCC,DIRECT} = [(F_{SN} + F_{AW} + F_{BN} + F_{CR}) \times EF_1] + [F_{OS} \times EF_2]. \quad (1)$$

F_{SN} is 90% of the synthetic N fertilizer applied the soil (kg N yr^{-1}), with 10% assumed directly volatilized before entering the soil. F_{AW} is 80% of the manure N applied to the soil (kg N yr^{-1}), with 20% assumed directly volatilized before entering the soil. F_{BN} is the N fixed by N-fixing crops (kg N yr^{-1}), calculated as 6% of the grain yield of soybeans and pulses. F_{CR} is the N in unburned crop residues returned to the field (kg N yr^{-1}). EF_1 is the direct

Table 2. Data requirements

	DNDC	IPCC
Weather	Daily minimum air temperature Daily maximum air temperature Daily precipitation Nitrogen deposition	None
Soils	Texture (clay content) pH Organic matter content	Area of cultivated organic soil
Agricultural Management	Individual crop areas[1] and crop rotations (including double cropping[2]) Synthetic N fertilizer use (type & timing)[3] Livestock & human populations[4] Tillage management[5] Irrigation management Planting and harvest dates Crop residue management[6]	Total cropland area Total harvest Synthetic N fertilizer use Livestock populations[4] Legume harvest

[1]Crops were barley, maize, cotton, millet, potato, rape oilseed, paddy rice, sorghum, sugarbeet, sugarcane, tobacco, winter wheat, spring wheat, green manure, small grains, and vegetables. [2]Double cropping rotations simulated were rice/rice, rice/winter wheat, rice/rape oilseed, maize/winter wheat. [3]Fertilizer mix assumption: 40% urea, 40% NH_4HCO_3, 20% $NH_4H_2PO_3$. [4]Animal and human populations were used to calculate manure additions to croplands. Baseline scenario assumptions were: 20% of livestock and 10% of human manure added to soil. Manure N production rates (kg N/head/yr): cattle – 50; horses/donkeys/camels – 40; sheep/goats – 12; swine – 16; humans – 4. [5]Tillage assumptions: 20 cm deep on planting day; 10 cm deep one day after harvest. [6]Base case scenario assumption was 20% of non-grain aboveground crop biomass returned to soil.

N_2O emission factor (0.0125±0.01 kg N_2O-N kg^{-1} N). F_{OS} is the area (in hectares) of cultivated organic soils (histosols), and EF_2 is an emission factor for cultivated organic soils (5–10 kg N_2O-N ha^{-1}). In our unofficial analysis, we excluded the F_{CR} factor because of difficulty in calculating this number after the simulations were completed. We also omitted the cultivated organic soil factor, as we did not have a good estimate of the area of cultivated histosols. We used our database values for synthetic N-fertilizer application, animal (cattle, sheep and goats, swine, horses, camels, and donkeys) and human populations, and used IPCC-recommended values for annual manure N production (kg N $head^{-1}$ yr^{-1}). In our DNDC simulations, we assumed 20% of animal manure and 10% of human manure was applied to the fields, so we used these same factors for our IPCC calculations. We included only the soybean areas in the F_{BN} term, as we did not have specific areas for pulses in our database, and we used the DNDC default value for optimum soybean grain yield (1320 kg C ha^{-1}). Thus our unofficial IPCC-formula estimate will be different from an official, more complete IPCC estimate, and is likely to be somewhat lower. Since the DNDC simulations calculate total N_2O emissions from a site, including background emissions, we added a 1 kg N_2O-N ha^{-1} yr^{-1} background emission (Bouwman, 1996) for each hectare of cropland ($A_{CROPLAND}$ = total area of cropland) to the IPCC-formula estimate, so that

$$N_2O_{\mathrm{BACKGROUND}} = A_{\mathrm{CROPLAND}} \times 1kgN_2O - Nha^{-1}yr^{-1} \quad (2)$$

and

$$N_2O_{\mathrm{TOTAL}} = N_2O_{\mathrm{IPCC,DIRECT}} + N_2O_{\mathrm{BACKGROUND}}. \quad (3)$$

Results

Our database contains 0.95 million km^2 of cropland area in mainland China for 1990. Virtually all cropland lies in the eastern half of China (Figure 4), with concentrations in Northeastern China (Heilongjiang,

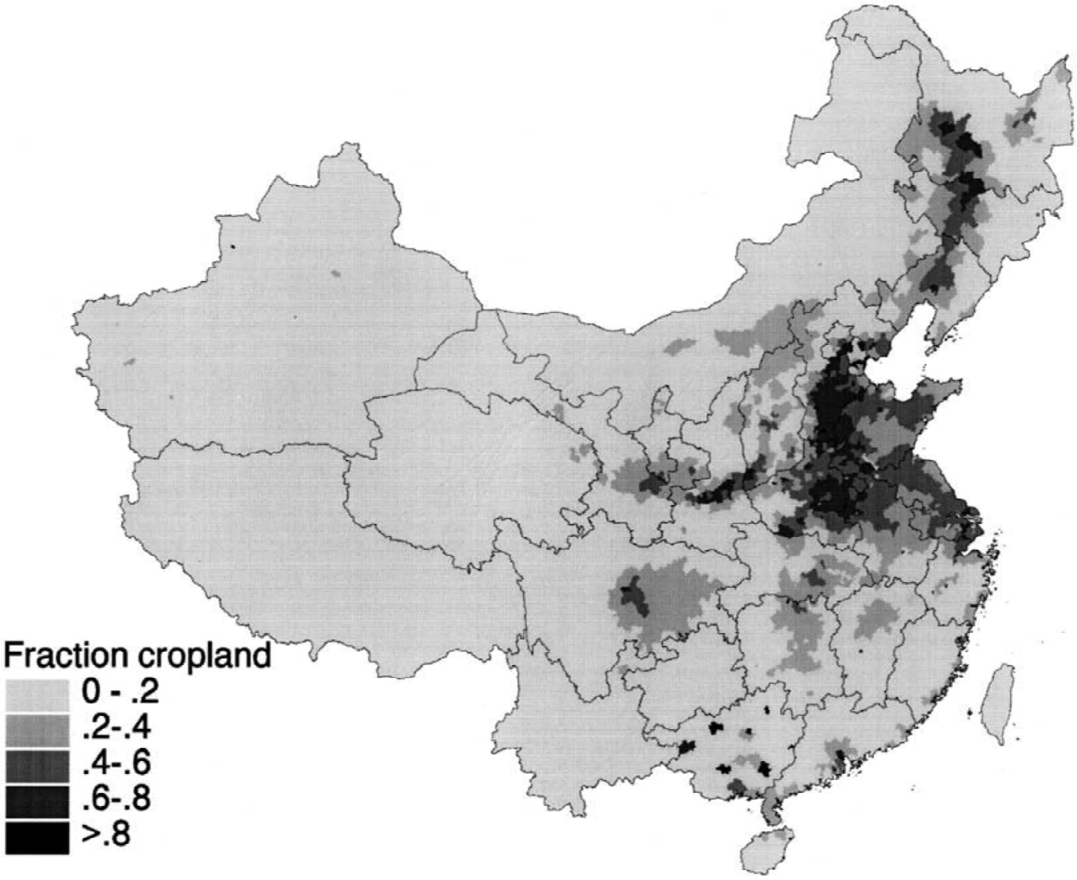

Figure 4. The percentage area of each county in mainland China that was cultivated cropland in 1990, according to the agricultural database of the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Map has provincial boundaries drawn. Cultivated land is concentrated in the broad plains and valleys of eastern China, and along the southern coast. Note that the database contains no data for Taiwan, yet.

Jilin and Liaoning Provinces), the North China Plain and Central China (Hebei, Shandong, Henan, Jiangsu, Zhejiang, Hubei, and Hunan Provinces), the Yellow River basin in Shanxi and Shaanxi Provinces, Sichuan Province in south-central China, and along the southern coast (Guangxi and Guangdong Provinces). Total sown area, which double-counts double-cropped areas, was 1.2 million km^2. Nitrogen fertilizer use had a similar pattern (Figure 5), though the North China Plain and Central China were more dominant. Total fertilizer use in China in 1990 was about 16.6 million tonnes N (16.6 Tg N). The national average fertilization rate was 175 kg N ha^{-1} cropland. Applying this fertilizer to the total sown area yielded an average application rate of 139 kg N ha^{-1} sown area.

Total N_2O emission for cropland in mainland China in 1990, as simulated by the DNDC model, was 0.31 Tg N_2O-N (Figure 6a). Highest county emissions were in northeastern China, the Sichuan Basin and the Yangtze River valley, and in southern China. Simulated county emission rates in the North China Plain were low, despite intensive agriculture (Figure 4) and significant fertilizer use (Figure 5). The mean N_2O flux rate for all cropland in mainland China was 3.3 kg N_2O-N ha^{-1} yr^{-1}, but rates for individual counties ranged from less than 1 kg N_2O-N ha^{-1} yr^{-1} to more than 8 kg N_2O-N ha^{-1} yr^{-1} (Figure 6b). The county-average percentage of N fertilizer lost as N_2O varied from less than 0.25% to greater than 4% (Figure 7), with a national average of 0.8%. Again, low percentage loss rates were primarily in the North China Plain (as well as arid western China). Note that many of the counties with high N_2O loss percentages in the western two-thirds of China are mountainous or high elevation plateaus with little cultivated cropland (see Figures 3 and 4).

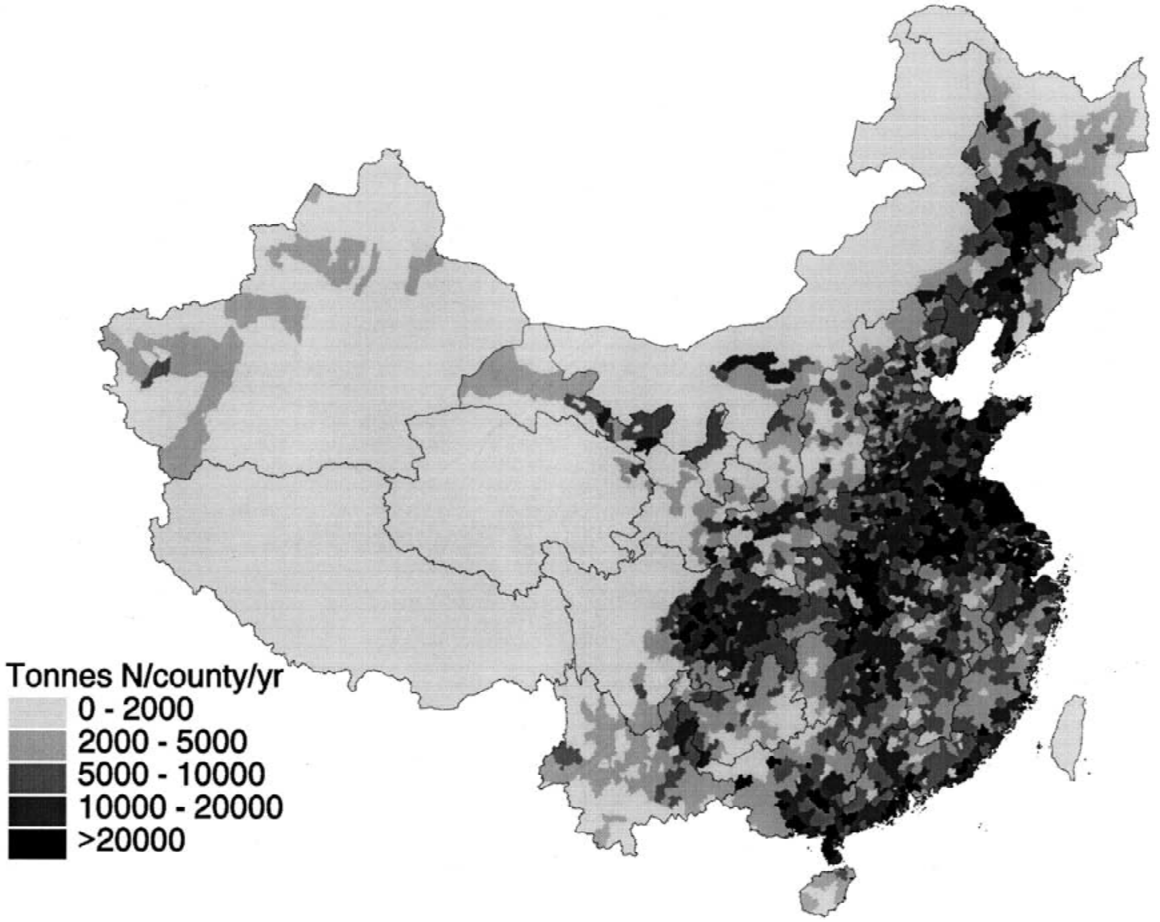

Figure 5. Total N-fertilizer use (Mg N) for each county in mainland China for 1990, from the same database as in Figure 4. The spatial pattern of fertilizer use is similar to the cropland distribution in Figure 4. Note, however, that this figure is total county loading of N-fertilizer and is thus a product of fertilizer application rate (kg N ha^{-1} yr^{-1}) and county cropland area. Mean fertilizer application rates for most counties were between 100 and 325 kg N ha^{-1} yr^{-1}. Total fertilizer use in China in 1990 was 16.6 Tg N. Note that the database contains no data for Taiwan.

Our application of the IPCC methodology (Equations 1–3) estimated 1990 total direct soil N_2O emissions for China at 0.36 Tg N_2O-N, 16% higher than the DNDC estimate. The IPCC value includes a background emission of 0.095 Tg N_2O-N, based on a rate of 1 kg N_2O-N ha^{-1} for 95 million ha of cropland, or 26% of the total flux. In the IPCC calculation N_2O emission due to synthetic N fertilizer 0.21 Tg N (58% of the total flux), while animal and human manure additions generated 0.048 Tg N (13% of the total flux) and biological N-fixation by soybeans contributed 0.008 Tg N (2%). DNDC simulations estimated a fertilizer-induced N_2O flux of 0.13 Tg N, 42% of its estimated total flux, and a manure-induced flux of 0.02 Tg N_2O-N, 6% of the DNDC total.

DNDC county-scale estimates of N_2O emissions were often less than 50% or greater than 150% of the N_2O emission estimate we calculated using the IPCC formulation (Figure 8). DNDC estimates of N_2O emissions were lower than the IPCC estimates for the major agricultural region of the east-central China and significant parts of Hunan and Sichuan Provinces. DNDC estimates of N_2O emissions were higher than the IPCC estimates for croplands in northeastern China, parts of Sichuan Province, Jiangxi Province in southeastern China, and many of the southern coastal counties.

Discussion

The process-oriented DNDC model estimated mainland China N_2O emissions from cropland by simulating daily emissions from all major cropping situations in each of 2500 counties in China. The total estimated

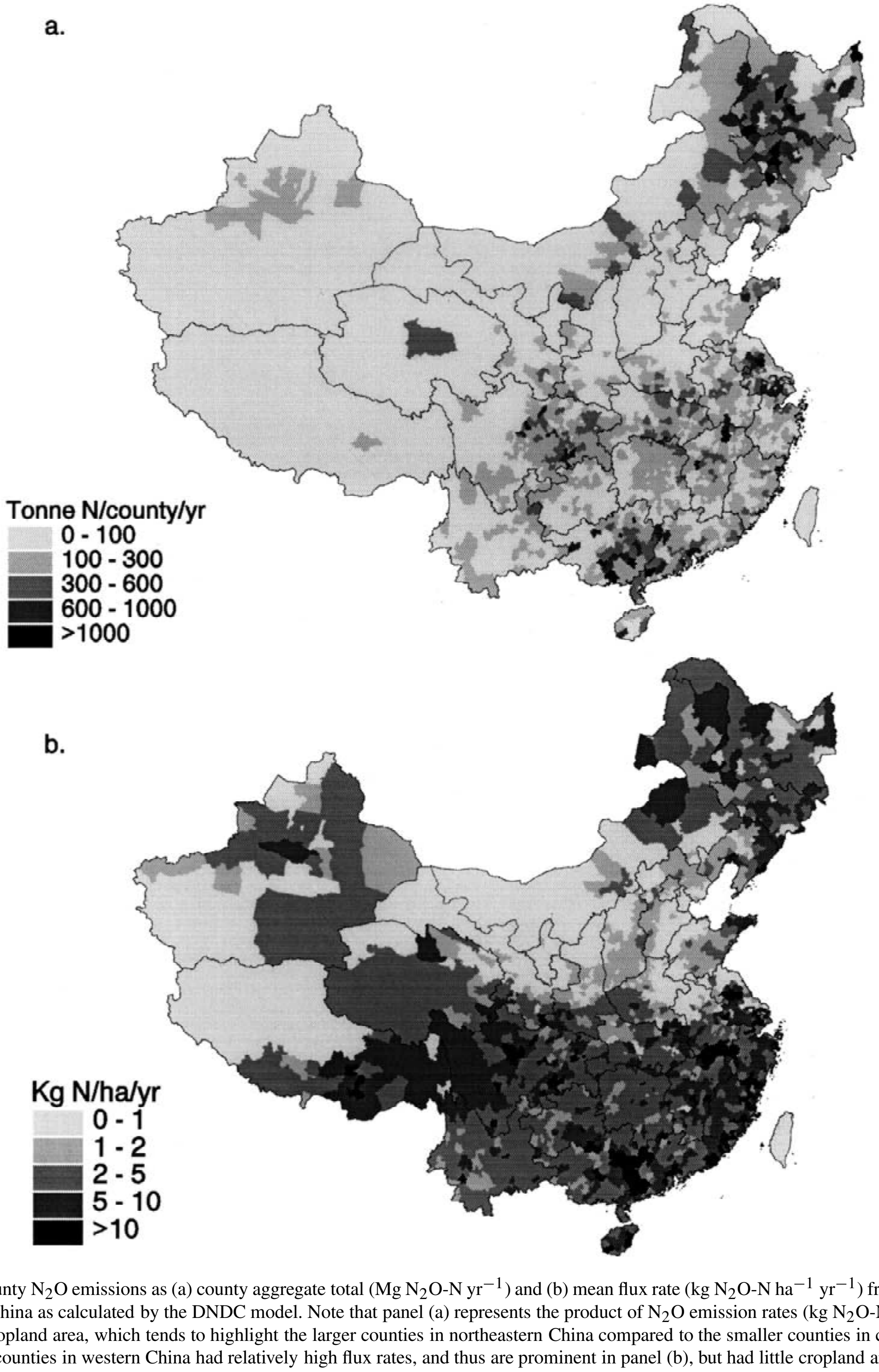

Figure 6. County N_2O emissions as (a) county aggregate total (Mg N_2O-N yr^{-1}) and (b) mean flux rate (kg N_2O-N ha^{-1} yr^{-1}) from croplands in mainland China as calculated by the DNDC model. Note that panel (a) represents the product of N_2O emission rates (kg N_2O-N ha^{-1} yr^{-1}) and county cropland area, which tends to highlight the larger counties in northeastern China compared to the smaller counties in central China. A number of counties in western China had relatively high flux rates, and thus are prominent in panel (b), but had little cropland area (Figure 4) and thus little total flux in panel (a). Note that the database contains no data for Taiwan.

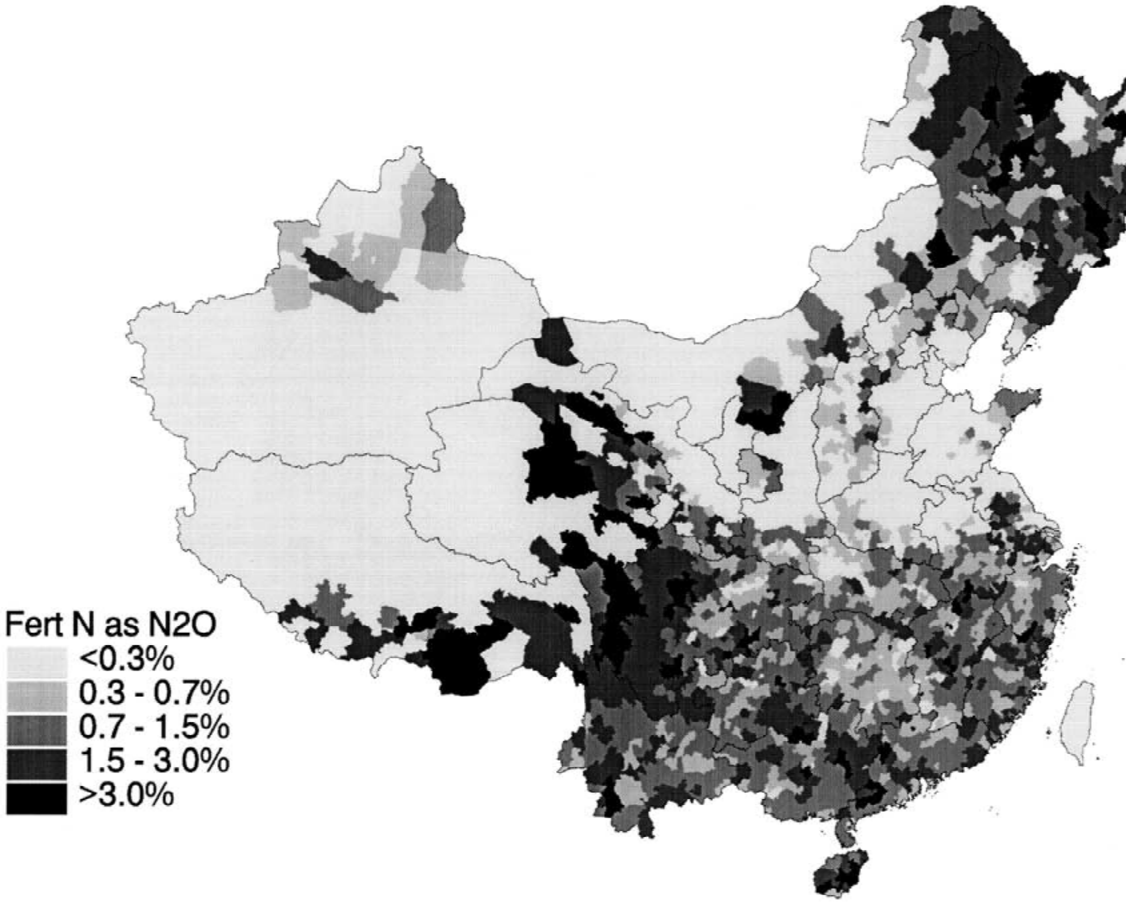

Figure 7. Percent of synthetic N fertilizer applied that is emitted as N_2O. This is calculated as the difference in N_2O emissions for DNDC simulations of the baseline scenario and a scenario with zero synthetic N fertilizer inputs. The 'fertilizer-induced' N_2O flux is divided by the synthetic N fertilizer input to get a percent loss. Percent N_2O loss rates are low in Central China, due to low soil fertility in this region, and higher in northern and southern China where soil organic matter contents are higher. Many of the counties with high percent loss rates in western China have very little agricultural land (see Figure 4). Note that the database contains no data for Taiwan.

flux using DNDC was 0.31 Tg N_2O-N. The IPCC has developed a national inventory methodology using a simple formula to estimate direct N_2O emissions from cropland based on nationally aggregated statistics. The total estimated flux using a nearly complete IPCC methodology was 0.36 Tg N_2O-N. This application of the IPCC methodology was incomplete because it excluded N_2O emissions resulting from incorporation of crop residue into the soil, and from the cultivation of organic soils. This application also included a background flux of 1 kg N_2O-N ha^{-1} yr^{-1} for all cropland. These two approaches can be compared to a third methodology used by Xing (1998) to estimate a 0.40 Tg N_2O-N emission from cropland in China for 1995. Taking into consideration published and unpublished field studies of N_2O emissions from cropland in China, Xing (1998) disaggregated total cropland into eight categories. Upland cropping in China was divided into three categories: regions with (1) one crop per year, (2) two crops per year or three crops per two years, and (3) two crops per year, five crops per two years, or three crops per year. Paddy rice agriculture was disaggregated into five categories: regions with (1) single rice, (2) rice-wheat, (3) double rice, rice-wheat, or double rice-upland crop; (4) double rice-upland crop or triple rice; and (5) single rice-continuous flooding. For each of the cropping categories, Xing multiplied field study estimates of annual N_2O emission by the area cropped. The total cropping area (China Agricultural Yearbook, 1996) was 0.95 million km^2 (0.70 million km^2 in upland crops and 0.25 million km^2 of paddy fields). Xing's estimate could be expected to be

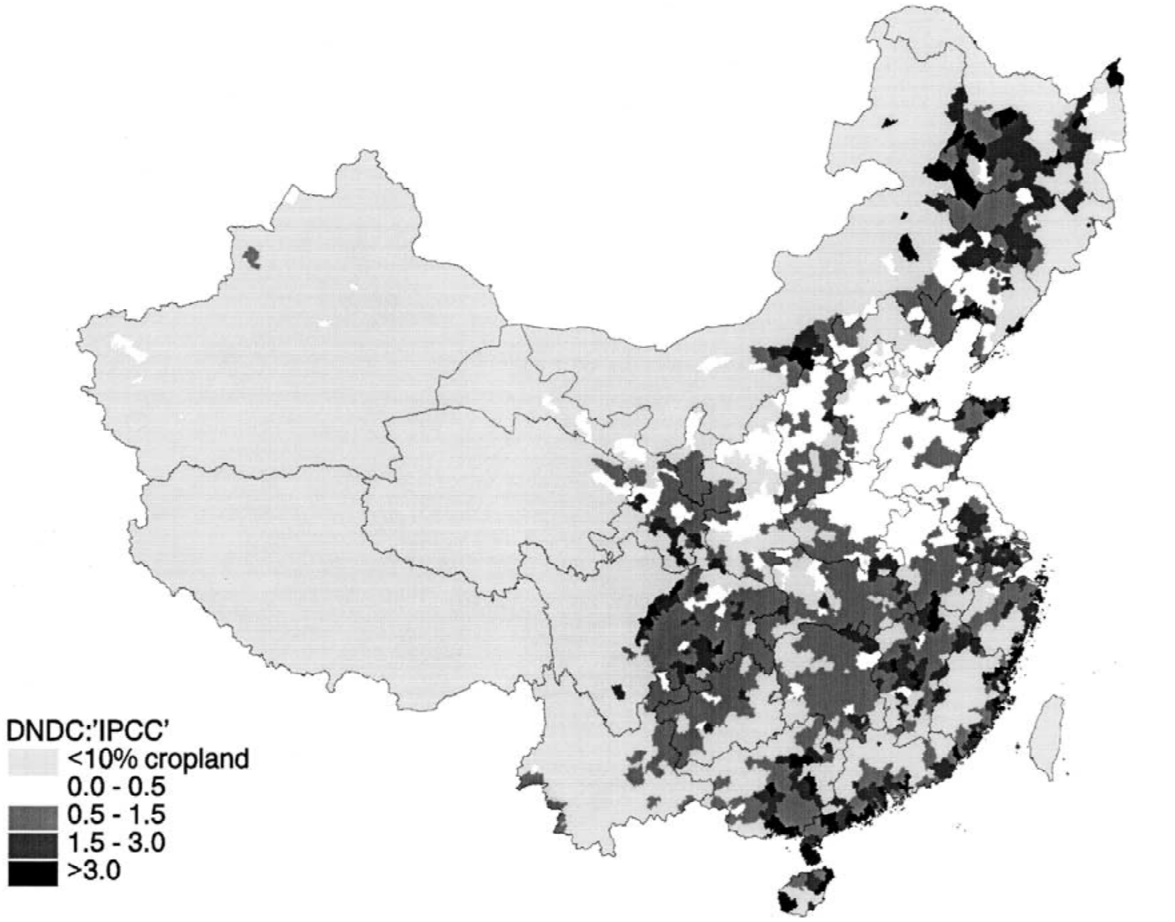

Figure 8. The ratio of DNDC N_2O emission estimates to estimates based on the IPCC methodology (see text for details of how this methodology was applied). To highlight agriculturally important areas, all counties with less than 10% of their land area in cropland (most of the western half of the country, see Figure 4) are set to the lowest category. Since uncertainty in both estimates is roughly ±50% (see text for discussion) DNDC:IPCC N_2O flux ratios of 0.5 to 1.5 are probably not significant disagreements. For many counties, particularly in the North China Plain, the ratio of DNDC to IPCC N_2O emission estimates is less than 0.5. For a number of counties in Northeastern China and along the southern coast, the ratio of DNDC to IPCC N_2O emission estimates is greater than 1.5. Note that the database contains no data for Taiwan.

higher than the DNDC and IPCC estimates because total N fertilizer use in China in 1995 was 20% higher than in 1990 (FAOSTAT, 1999). This increase in N fertilizer use would raise the IPCC methodology estimate to 0.40 Tg N_2O-N, and would raise the DNDC estimate to 0.34 Tg N_2O-N, if DNDC's national average of an 0.8% loss rate as N_2O is assumed for the additional fertilizer.

All three of these estimates have at their core empirical data on N_2O fluxes. The process algorithms in the DNDC model have been developed and parameterized using data collected in field and laboratory studies performed by a number of research groups in a number of locations, including two sites in China. The goal of process modeling is to include robust parameterizations of key processes so that the effects of process interactions and feedbacks can be simulated in a range of settings and conditions. The IPCC methodology is based on a global parameterization where a number of published field studies were analyzed, and simple, linear relationships between various nitrogen inputs and N_2O emissions were developed. The methodology does not consider any potential interactions or feedbacks between various components of the nitrogen cycle, nor the potential impacts of any agricultural management other than total N additions (e.g., tillage, irrigation, type or timing of fertilizer application). The methodology is intended to be general and broadly applicable, but is not intended to be a good predictor of behavior at any particular site. The

IPCC parameterization used here was not specific for China. In fact, the IPCC encourages countries to replace default parameters with country-specific values if local research indicates that this will improve the assessment (IPCC, 1997). Xing (1998) based his estimate only on published data of N_2O emissions from about 15 field studies in China. His methodology did not include any details about the nitrogen cycle in agroecosystems, and, using all available data, had to assume that the sites measured were representative of all cropland in China.

The DNDC analysis also required spatially referenced datasets for China: political boundaries, soil properties, crop areas, agricultural management, and weather data (Table 2). Assembling these datasets was a major part of the research effort. The IPCC methodology requires only a few nationally aggregated statistics, as does Xing's methodology. The premise of the IPCC methodology is that mean N_2O flux rates based on a global data set ($\sim$100 sites) will probably be reasonably representative of emissions at the national scale for most countries. Xing's premise is that N_2O flux rates measured in a range of agro-ecosystems in China ($\sim$15 sites) can be extrapolated to generate a national emission estimate for China. Xing (1998) states, however, that a larger database would improve the estimate, as China is a large country with a diverse agro-ecosystem landscape, and it is poorly sampled for N_2O fluxes. The premise of the DNDC model is that by modeling the processes that lead to N_2O fluxes, a model can make reasonable estimates of emissions from a range of agro-ecosystems.

All three estimates of N2O emissions from cropland in China involve significant uncertainties. For the DNDC model, the results reported above are the mean of high and low estimates which we believe put reasonable bounds on the likely emissions values. The DNDC high estimate (based on simulations with high SOC values) was 0.44 Tg N_2O-N; the DNDC low estimate was 0.18 Tg N_2O-N. The DNDC estimate could be reported as 0.31 ± 0.13 Tg N_2O-N, with an uncertainty of about $\pm40\%$. Although the current IPCC methodology does not include a formal uncertainty analysis, all emission factors are recommended as a mean value and a range. The IPCC emission factor is $1.25\pm1.0\%$ for nitrogen applied to a field as synthetic fertilizer, manure, crop residue or due to biological N fixation (IPCC 1997). Applying the high (2.25%) emission factor generates total emissions (including background) of 0.57 Tg N_2O-N; the low emission factor (0.25%) yields 0.15 Tg N_2O-N. This gives a range of about $\pm60\%$ around the median IPCC estimate of 0.36 Tg N_2O-N. Xing (1998) does not report associated uncertainty estimates for any of the field studies used to get annual emission rates for different crop/management regimes, so no uncertainty estimate can be generated. However, an uncertainty estimate for field-scale estimates of annual N_2O emissions based on chamber measurements is not likely to be less than $\pm50\%$ (Smith et al., 1994; Crill et al., 2000), i.e., comparable to the uncertainties associated with the DNDC and IPCC estimates.

A significant uncertainty in the national inventory estimates made with DNDC and by Xing (1998) is the actual cropland area. China's 1990 cropland area in our database and used by Xing (0.95 million km^2) is within 1% the national total provided by China's State Statistical Bureau (SSB) in their annual report (e.g. SSB, 1994). However, the SSB states, 'Figures for the cultivated areas are under-estimated and must be further verified' (SSB, 1994, p. 329); this under-reporting is probably also true for our database (Zhuang et al., 1996). Recent estimates are that actual cropland is 15–50% greater than reported by the SSB, with regional and crop type variations (Crook, 1993; Fu et al., 1993). Several recent estimates of arable land area include: Fischer et al. (1998) – 1.23 million km^2; the Food and Agricultural Organization of the United Nations (FAOSTAT, 1999) – 1.24 million km^2; Wu (1990) and Wu and Guo (1994) – 1.36 million km^2. Some of the difference between estimates may be due to differences in categories. The SSB and our databases refer to planted cropland, while the FAO definition of arable land includes 'temporary meadows for mowing or pasture' and 'land temporarily fallow (less than 5 years)' (FAOSTAT, 1999). This broader cropland definition may also apply to estimates of Fischer et al. (1998) and Wu and Guo (1994).

In the DNDC analysis, working with a larger cropland area would probably lead to higher total N_2O emissions. However, it would also reduce synthetic fertilizer and manure application rates (the same amounts applied to more land area), which might change the amount of applied N lost as N_2O. Using a larger cropland area in the Xing (1998) analysis would lead to greater N_2O emissions. In both the DNDC and Xing analyses, the change in N_2O flux resulting from using a different cropland area dataset would depend on which cropping categories had the biggest area changes. For example, N_2O flux rates used by Xing (1998) range from zero, for 'single rice – continuous flooding', to 5.12 kg N_2O-N ha^{-1} yr^{-1} for 'two crops per year, five crops per two years, or three crops per year.' In the formal IPCC methodology, cropland area does not enter the calculation, so the IPCC estimate would not change if cropland area were increased. The background flux used in our calculation would increase (Equation 2), but the increase would be independent of crop category.

Countries seeking to lower their N_2O emissions from agriculture may wish to explore the consequences of various mitigation strategies. In the IPCC methodology, this can only be done at an aggregate, national scale, and as Equation 1 is a simple, linear model, the consequences of mitigation strategies (e.g., reducing synthetic N fertilizer use by 25%) are straightforward. With a process-oriented model, many more mitigation strategies can be explored in much greater detail. For example, a nation could evaluate the consequences not only of changing fertilizer amounts, but also of changing the mix of N fertilizers (e.g., replacing urea with ammonium nitrate), and/or of changing the timing and method of N fertilizer application. In addition, a detailed analysis with a process model can indicate which crops and/or regions in a country have the greatest N_2O emission rates, so mitigation efforts could be focussed most effectively. For example, DNDC estimated a highly variable pattern of the percentage of N fertilizer emitted as N_2O. This would suggest that mitigation strategies be a higher priority in northeastern and southern China than in central China (Figure 7). Simulated emissions were lower in central China primarily because of lower soil fertility in that region. A second factor in the lower emission rates was probably that this region is semi-arid, with lower precipitation than in Northeast China or Southern China. The IPCC methodology, on the other hand, would focus mitigation on regions with high fertilizer use, particularly central China (Figure 5). A process model can also predict other consequences of potential mitigation strategies, particularly impacts on crop yield. Furthermore, in the IPCC methodology, the consequences of future climate change scenarios on N_2O fluxes cannot be estimated. A DNDC set of simulations with a warming of +2 °C for all of China resulted in a 10% increase in total N_2O emissions.

The full IPCC methodology for N_2O emissions from agriculture includes two categories of emissions not yet discussed, direct emissions from animal production and indirect emissions from nitrogen used in agriculture (IPCC, 1997). Direct N_2O emissions from animal production come primarily from animal waste management (storage and treatment). The primary source of indirect N_2O emissions is nitrification and denitrification of excess nitrogen that leaves croplands via surface runoff or leaching out of the root zone. Mosier et al. (1998) estimate that at the global scale, both of these additional categories of N_2O emissions contribute as much as direct soil emissions, each totaling 2.1 Tg N_2O-N yr^{-1}. No process-oriented agroecosystem model includes a thorough analysis of all three categories of N_2O emissions.

Conclusions

The process-based DNDC model and the strictly empirical IPCC methodology gave similar estimates of direct N_2O emissions from cropland soils in China in 1990. DNDC estimated total emissions at 0.31 Tg N_2O-N, and our application of the IPCC methodology estimated total emissions (including background) at 0.36 Tg N_2O-N. Both these estimates were lower than that of third methodology applied by Xing to estimate 1995 emissions (Xing, 1998), but when adjusted for increased fertilizer use from 1990 to 1995, all three estimates were in reasonable agreement (0.34-0.40 Tg N_2O-N). Uncertainty in all estimates is probably on the order of ±50%. Mosier et al. (1998) estimated the global total of direct N_2O emissions from cropland soils at 2.1 Tg N_2O-N.

Fertilizer-induced N_2O emissions were calculated with the DNDC model by subtracting fluxes from a zero-fertilizer run from the baseline scenario fluxes. Total fertilizer-induced N_2O emission for China was 0.13 Tg N_2O-N, 0.8% of the 16.6 Tg N applied in synthetic fertilizers in 1990. This falls within the range of the IPCC's recommended factor of 1.25±1.0%. However, percent fertilizer loss was quite variable from county to county in the DNDC simulations, ranging from less than 0.25% to greater than 4%. The primary cause of this was variability in soil organic matter (SOM) content, with higher SOM leading to higher simulated N_2O fluxes. These variable percentage loss rates caused DNDC to generate very different patterns of N_2O emissions across China than did the IPCC methodology, also applied at the county scale. These different patterns would lead to different mitigation recommendations. DNDC results would focus mitigation efforts on regions with high percentage flux rates, where there is likely to be more potential for reducing N_2O emissions without reducing crop yields. A more detailed analysis of the simulation results may indicate particular crops or crop/soil/management combinations that are best candidates for mitigation efforts.

Based on the analysis presented above, the IPCC methodology appears to be adequate for generating national inventories of N_2O fluxes, though similar comparisons should be made for other countries, with different soils, climate, and agriculture, before any broad conclusions are reached. If nations wish to explore the consequences of various mitigation strategies, both in terms of N_2O production as well as crop yield, process-oriented models will be necessary tools. Since all inventory methodologies have empirical observations at their core, further analysis and incorporation of more field data will improve our ability to estimate direct N_2O emissions at these scales by any method.

Acknowledgements

This work was supported by a grant from the Terrestrial Ecology Program, jointly supported by NASA, NSF, EPA, DOE, and the USDA; by the Chinese Natural Science Foundation under contract number 39790100; and also by a grant from the NASA EOS Interdisciplinary Science Program. We thank Denise Blaha, Michael Routhier, Stanley Glidden, and Qinghua Lin for help with the database preparation, Ye Zhou for help with the DNDC modifications, and Steve Boles for help with GIS work.

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