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Quantifying nitrous oxide emissions from Chinese grasslands with a process-based model

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Abstract

As one of the largest land cover types, grassland can potentially play an important role in the ecosystem services of natural resources in China. Nitrous oxide (N_2O) is a major greenhouse gas emitted from grasslands. Current N_2O inventory at regional or national level in China relies on the emission factor method, and is based on limited measurements. To improve inventory accuracy and capture the spatial variability of the N_2O emissions under the diverse climate, soil and management conditions across China, we adopted an approach that uses a process-based biogeochemical model, DeNitrification-DeComposition (DNDC) in this study, to map the N_2O emissions from China's grasslands. The DNDC was linked to a GIS database of spatially distributed information of climate, soil, vegetation and management at county-level for all grasslands in China. Daily weather data from 2000–2007 based on the national network of 670 meteorological stations were utilized in the model simulations. The results were validated against observations from several grasslands in China and from other countries. The modelled results showed a clear geographic pattern of N_2O emissions from China's grasslands. A high-emission strip was found that stretched from northeast to central China, along the eastern boundary of the temperate grassland region adjacent to the major agricultural regions. The grasslands in the western mountain regions, however, emitted much less N_2O. The regional average of N_2O emission rates was 0.23, 0.11 and 0.39 kg N ha^{-1} y^{-1} for the temperate, montane and tropical/subtropical grasslands, respectively. The national N_2O emission was 76.5 Gg N from the 337 million ha of grasslands in China. The modelled results were in good agreement with observations ($R^2 = 0.64$ for 11 datasets), suggesting that the process-based model can be used to capture the spatial dynamics of N_2O emissions as an effective alternative to statistical method currently used in China.

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the global average surface temperature has increased by around 0.74 ± 0.18 °C during the 20th century, and global atmospheric concentrations of greenhouse gases (GHGs) have increased markedly as a result of human activities since 1750 (IPCC, 2007). Increased GHG emissions have altered the energy balance of the climate system and are one of the major causes of climate change (IPCC, 2007). On a global basis, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), contribute 60, 15 and 5%, respectively, to the anthropogenic GHGs' effect (Rodhe, 1990). The instantaneous flux rates of the GHGs were important clues to lead an accurate assessment of the terrestrial ecosystem contributions to climate change (Du et al., 2008). N_2O is a major contributor to global warming because of its long atmospheric lifetime and large radiative forcing potential (Cicerone, 1989; Mummey et al., 2000; IPCC, 2007); however, large uncertainty exists about the global N_2O budget (Bouwman et al., 2000; Chapuis-Lardy et al., 2007). Grasslands, where herbaceous plants form the dominant climax community (Coupland, 1992; Mummey et al., 2000), play a significant role in the regional climate and global carbon cycle both in tropical and temperate regions (Scurlock and Hall, 1998). However, compared with forest ecosystems, little attention has been paid to N_2O exchange in grassland ecosystems, despite the fact that grassland covers about one-fifth of the world's land surface and about 40% of China's national land cover (Allard et al., 2007; Kang et al., 2007). It is important, therefore, to quantify N_2O emissions from grasslands for more accurate assessment of the N_2O budget (Mummey et al., 2000) and to gain a better understanding of the potential N_2O production and emission processes in grassland ecosystems for future climate change mitigation (Guo and Zhou, 2007).

The IPCC method was frequently used to estimate N_2O emissions although less capable of quantifying impacts of climate or management on the gas fluxes. Consequently process-oriented models were proposed to improve N_2O emission estimates (Boeckx and Van Cleemput, 2001). At a national scale, process-based models have proven useful in reducing uncertainty and helping understand the complex biogeochemical processes involved in trace gas production (Barnsley, 2007). Spatially distributed process-oriented models have also been effective in achieving this objective (Chen et al., 2008), which is the focus of this paper.

Grassland is widely distributed in north and northwest China (Kang et al., 2007), and is under threat of serious degradation and over grazing. Increasing numbers of scholars have advocated changing grassland management and adopting intensive management (Nan, 2005). Grassland management practices have recently undergone some significant changes over the past decades because of economic development (Chen and Chen, 2007). To slow down degradation and maintain sustainability, some grassland laws have been introduced and some management practices were promoted by the Chinese central government (Chen and Chen, 2007; Unkovich and Nan, 2008). These include converting reclaimed land to pasture lands, practicing rotational grazing method using fencing; promoting conservation practices; tending and controlling rodents and insect pests; promoting rangeland improvements such as shallow-ploughing, fertilization and irrigation; and promoting restorations such as aerial-sowing, cultivation practices, converting cultivated lands to pastures, and establishment of a forage base (Yang, 1992; Chen and Chen, 2007). Among of them, fertilization and improved grazing management practices are the most adopted options (Conant et al., 2001). These management options tend to have the potential to change the spatial distribution of N_2O emissions, thus making the national estimation of N_2O difficult. Therefore, the preliminary researches indicated that the magnitudes of N_2O fluxes from Chinese grassland varied greatly in space and time (Du et al., 1997, 2006; Dong et al., 2000; Xu et al., 2003). There is a need to use spatially explicit process-based models to account for the dynamic nature of grasslands in China in order to arrive at a more accurate estimate of the N_2O emissions at the national level.

The objective of this study was to estimate N_2O emissions and their spatial distributions across the grasslands in China using a spatially explicit process-based DNDC model, with a goal of improving the national estimate of N_2O emissions. We adopted a

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four–phase method that includes (1) database development, (2) scaling up, (3) model validation and (4) sensitivity analysis.

2 Method

2.1 Database development

To apply DNDC at a national scale, we developed a GIS database to store the spatially distributed information of climate, soil and grassland types. Counties were used as the basic unit for the simulation. The database contained 2368 counties, excluding those with small areas less than 500 square kilometres. The database consisted of: (1) 18 grassland types with growth properties (e.g. maximal production, maximal height, and root/shoot ratio); (2) soil properties (e.g. maximum and minimum soil surface organic carbon content, bulk density, clay fraction and pH); (3) daily climate data (e.g. maximum and minimum air temperatures, and precipitation); and (4) areas and geographic locations of grassland types at county level. These data were obtained from the Commission for the Integrated Survey of Natural Resources; the Institute of Soil Science, Chinese Academy of Sciences; and the Chinese Meteorological Administration.

2.1.1 Grassland dataset

There is a large uncertainty concerning the total grassland area in China. Fang et al. (1996) estimated 569.9 million ha based on agricultural atlases and land use maps of the 1980s. Ni (2001) used 405.9 million ha in his report, and Fan et al. (2008) estimated 331 million ha of grassland area. Because of the large discrepancies, in this study, we digitized the 1:1 000 000 grassland resource maps (Commission for Integrated Survey of Natural Resources, 1995), and classified all grasslands 18 vegetation types, according to Ni (2002). Considering the extensive changes in land use over the last decade in China (Lin and Ho, 2003), we applied the 1:100 000 National Land Cover

Dataset (NLCD) of China acquired in 1999 and 2000 to modify the grassland area by retaining only those areas identified as grassland in the NLCD. The final grassland area of our new database was 336.98 million ha (Fig. 1).

2.1.2 Soil dataset

We used a 1:1 000 000 scale soil database developed by the Institute of Soil Science, Chinese Academy of Sciences, which was compiled based on the second national soil survey conducted in 1979–1994 covering all the counties. The database contains three attributes: locations, attributes, and reference systems. It contains multi-layer soil properties (e.g. organic matter, pH and bulk density), soil texture (sand, silt and clay) and spatial information (Shi et al., 2004; Yu et al., 2007). In this study, we used data in the upper 0–10 cm soil profile as the soil surface properties for model simulations.

2.1.3 Climate dataset

We used 10 km-resolution daily national climate data from 2000–2007, which were interpolated from 670 meteorological stations using Ordinary Kriging method. The climate data included daily precipitation, maximum and minimum temperatures (http://data.cma.gov.cn/).

2.1.4 Grazing data

Based on the statistical data in 2000 at the national scale from the National Bureau of Statistics of China (NBSC, http://www.stats.gov.cn/english/statisticaldata/), we assumed that the grasslands in China experienced a similar grazing practice, and livestock was evenly distributed among all grasslands. The average national grazing stock value was applied (total livestock divided by total area). Specifically, the grazing stocks were 0.32, 0.06 and 0.72 head/ha of cattle, horses and sheep, respectively, and no fertilizer application was assumed.

2.2 Model upscaling

To estimate the national N_2O emissions from grasslands in China we linked DNDC to the database containing climate data (2000–2007), soil properties and grassland types and total grassland area. Because SOC content was one of the most sensitive factors affecting N_2O fluxes, we ran the DNDC model for each grid-cell with the maximum and minimum SOC content values to quantify the uncertainty in the upscaling (see details in Li (2007). Then, the eight years of N_2O emission average rates were reported and compared with field and previously published results.

2.3 Model validation

DNDC is a process-based model of carbon and nitrogen biogeochemistry for terrestrial ecosystems. The model was originally developed for estimating N_2O emissions from agricultural ecosystems (Li, 1992a, b; Li et al., 2004). Detailed processes of nitrification and denitrification were built in the model to track the kinetic processes of N_2O production and consumption driven by the soil climate and substrate concentrations (Li, 2007). DNDC consists of two main components. The first component consists of soil climate, crop growth and decomposition sub-models converts primary drivers such as climate, soil, vegetation and human activities into soil environmental factors (e.g. soil temperature, humidity, pH, Eh and substrate concentration gradients). The second component of DNDC includes nitrification, denitrification and fermentation sub-models calculates N_2O and CH_4 production and consumption (Li, 2000; Li et al., 2000). The DNDC model has been successfully tested and applied for N_2O inventory in many countries across climatic zones, soil types and management regimes (Frolking et al., 1998; Li, 2000; Li et al., 2000, 2001, 2005; Saggar et al., 2004; Beheydt et al., 2007; Saggar et al., 2007), and is recognized as one of the most widely used N_2O models in the world (Chen et al., 2008). DNDC has been also applied in China for estimating N_2O emissions from grassland at the site-scale (Xu et al., 2003).

We further tested DNDC for its applicability to grasslands in China. Ten grassland sites, including eight in China and two in the United States, where N_2O fluxes were measured and the annual emission rates were reported in publications (Table 1) were used for validation tests. The sites were natural grasslands as defined by Coupland (1992) without any fertilizer applied. The modelled annual N_2O emissions rates were consistent with reports for the sites (Fig. 2), except for the alpine meadow (Du et al., 2008) for which the modelled N_2O flux was only 1/10 of observation. However, Du's observed values were higher than that reported by other researchers for montane grasslands in China (Pei et al., 2003, 2004) or other countries (Mosier et al., 1993), and was also higher than that from fertilized grassland in Europe (Levy et al., 2007). The high N_2O emissions from the site of Du et al. (2008) could be related to its high soil moisture and high emissions from plants.

2.4 Sensitivity analysis

The sensitivity analysis was conducted by varying a single model input parameter in a predefined range, which was commonly observed in a unit of study, while keeping all other input parameters constant. Simulated annual N_2O flux sensitivities were evaluated for soil factors (i.e. pH, soil texture and soil organic C content), grazing intensity, and climate (i.e. precipitation and temperature). The baseline simulation was done using the average values of the entire grassland region (Table 2). The sensitivity tests were done to assess the model responses to soil attributes, management options, and climate variables

3 Results and Discussion

3.1 Model sensitivities to environmental variables

Table 2 lists the parameters in the sensitivity analysis. It is clear that the model responded to changes in both environmental factors as well as to human management options. This suggests that the model can be used to assess how climate change and human management practices affect N_2O emissions from the vast grasslands in China.

3.2 Sensitivity to soil attributes

The modelled N_2O emission rates were well correlated with the initial soil organic carbon (SOC) contents (Fig. 3c), which is similar to what was reported by Babu et al. (2006). Variation of initial SOC content showed significant effects on production and emission of N_2O. More N_2O gas was produced at pH 7 than from alkaline soils (Fig. 3a). Soil texture was also a sensitive factor due to its effects on soil aeration status; sandy loam soil was more likely to produce N_2O than clay soil (Fig. 3b).

3.3 Sensitivity to management options

The modelled N_2O emission was very sensitive to grazing management options, such as grazing intensity and duration. Enhanced grazing intensity increased N_2O emissions (Fig. 3d, e). The result was in agreement with that reported by Flechard et al. (2007). Nitrogen deficit is one of the major factors limiting grass growth in most Chinese grasslands (Nan, 2005; Unkovich and Nan, 2008). When fertilizer application rates increased from 0 to 45 kg N ha^{-1}, N_2O emissions increased from 0.1 to 0.25 kg N ha^{-1} y^{-1} (Fig. 3f).

3.4 Sensitivity to climate conditions

The N_2O emissions were susceptible to changes in rainfall and temperature, which is in agreement with previous studies that have shown the N_2O emissions were positively correlated with air or soil temperature (Yamulki et al., 1997; Dong et al., 2000). In this study, precipitation was either increased or decreased by 20% of the baseline value (520 mm y^{-1}). Increases in precipitation elevated N_2O emissions (Fig. 3g). Modelled data showed that the high precipitation stimulated denitrification, which is a major process producing N_2O and embedded in DNDC. The effect of temperature was examined

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by running a sequence of simulations with daily temperatures at 1 or 2 °C increment; N_2O emissions did not follow a simple relationship with change in temperature. With an increase of 1 °C in daily temperature, the N_2O emissions did not change; but when the increase was 2 °C, the total N_2O emission changed significantly (Fig. 3h). When temperature decreased, N_2O emissions also decreased clearly, since a decrease in temperature decreased the rate of organic matter decomposition and therefore decreased nitrification, which is an important source of N_2O (Li et al., 2000).

3.5 National inventory of N_2O emissions from China's grasslands

Based on the modelled annual N_2O-fluxes for the eight years (Table 3), a multi-year average N_2O emission value was calculated for each grid-cell as well as for all grasslands in China. The mean annual N_2O emission rates from all the grasslands were $<$ 0.5 kg N ha^{-1} y^{-1} with the highest for swamp grassland and the lowest for Alpine desert grassland (0.48 and 0.02 kg N ha^{-1} y^{-1}, respectively) and the national average 0.22 kg N ha^{-1} y^{-1}. National inventory of N_2O emissions from Chinese grassland was calculated based on the area and N_2O emission rates for each type of grassland (Table 3). The results showed that the 337 million ha of grasslands in China emitted 76.5 Gg N_2O-N y^{-1} on a multi–year average basis.

The modelled N_2O fluxes were analyzed by combining the 18 types of grassland into three categories based on ecological climate zone. The three categories were temperate grasslands, montane grasslands and tropical/subtropical grasslands (Table 4, Fig. 4). Each of the three categories possessed specific features and was basically consistent with climate patterns. The greatest N_2O flux (0.39 kg N ha^{-1} y^{-1}) occurred in the tropical/subtropical grassland region, in which both moisture and temperature were more favourable for N_2O production. In the montane grassland region, the average N_2O flux was the lowest at 0.11 kg N ha^{-1} y^{-1}; this region is humid but with low temperature. The temperate grassland region had a medium emission flux, averaging 0.23 kg N ha^{-1} y^{-1}. Even though the temperate grassland's N_2O flux rate was in the mid-range, it comprised 49% of the 337 million ha of total grassland area in China (Table 4), and thus this category's contribution is large, accounting for 57% of national emissions. Despite the large amount of montane grasslands (39% of the total grassland area in China), due to the lower N_2O emission rate, it only contributed 24% of the total N_2O flux. The tropical/subtropical grasslands occupy only 12% of total grassland areas, but account for 19% of the total N_2O flux.

3.6 Spatial and temporal distribution of N_2O emissions

The spatial distribution of the grassland N_2O fluxes was basically consistent with the climate patterns. In China, mean annual precipitation and temperature tend to decrease from east to west and from south to north. N_2O flux rates also followed this climate change trend, gradually decreasing from eastern to western regions. In the western high-altitude region, the N_2O flux rates were lower than in the eastern and southern region, especially in eastern Inner Mongolia and the sparsely distributed grasslands of the south, where the N_2O flux (Fig. 5) was higher.

On the national scale, during 2000–2007 the annual N_2O emission rate fluctuated year-to-year, and had an increasing trend (Fig. 6). In 2001 and 2005, the modelled national N_2O emissions were higher than in other years. In 2005, the total N_2O had an abrupt emission peak compared with other years. We compared the accumulated annual temperature >0 °C and the annual accumulated precipitation between 2005 and 2001 (Fig. 7a, b). These comparisons suggested that climate change seems to be the main reason for increased N_2O emissions. In the northern grassland region, the precipitation and the temperature significantly increased (Fig. 7a, b), which is believed to have caused the N_2O emissions increase. Another reason was that temperate grassland had a higher base emission rate than other types of grassland.

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3.7 Comparison of N_2O with worldwide grassland

In China, most grasslands are located in semi-arid and arid areas, which are classified as ecologically fragile zones (Liu, 2001). The poor soils and low precipitation could limit N_2O emissions due to the depressed nitrification and denitrification processes. However, some grasslands such as meadow and swamp grasslands have relatively high humidity and the modelled N_2O fluxes were relatively high in these areas. To estimate the reliability of our modelled results, we compared our modelled N_2O fluxes with those reported for other parts of the world, based on the similarity in grassland types.

3.7.1 Comparison with North American grasslands

The temperate grassland in Inner Mongolia was similar to the North Great Plains grassland in the US. The two grasslands are located at similar latitudes. Mummey et al. (2000) reported 0.24 kg N ha^{-1} y^{-1} emitted from Great Plains grassland, and Mosier et al. (1996) reported 0.1–0.2 kg N ha^{-1} y^{-1} based on long-term experiments in Colorado. These values were very similar to our 0.23 kg N ha^{-1} y^{-1} for temperate grassland in China. For the subalpine meadow experiment site in the US, values were 0.11 and 0.22 kg N ha^{-1} y^{-1} for 1991 and 1992, respectively (Mosier et al., 1993), for China's similar montane grasslands, this value was 0.11 kg N ha^{-1} y^{-1}. The comparisons indicate that the DNDC estimated values were within reasonable ranges.

3.7.2 Comparison with European and New Zealand grasslands

About 40% of the agricultural land in Europe is grassland. Some grasslands are tilled and reseeded to support productive grass species (Pinto et al., 2004). Flechard et al. (2007) reported a mean emission of 0.93 kg N ha^{-1} y^{-1}, higher than the 0.23 kg N ha^{-1} y^{-1} we modelled for China's temperate grassland. However, Flechard et al. (2007) pointed out that intensively managed systems emitted more N_2O than

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the extensive management grasslands in Europe. Allard et al. (2007) also reported the extensive grassland (similar to natural grassland) had a lower N_2O emission rate (average 0.13 kg N ha^{-1} y^{-1}) which is close to results from China's grasslands.

Fertilizer use is common for European semi-natural grassland as well as grassland in New Zealand that leads to high N_2O emissions (Boeckx and Van Cleemput, 2001; Saggar et al., 2004, 2007; Levy et al., 2007). In China, grasslands are sparsely fertilized or irrigated (Huang et al., 2003; Nan, 2005; Unkovich and Nan, 2008).

3.7.3 Comparison with African grassland

Savannahs are the most widespread vegetation in Africa (White, 1983; Rees et al., 2006), and the grass species in savannahs are quite different from those in temperate grasslands (http://www.bcgrasslands.org/library/world.htm). Brummer et al. (2008) found that in an African savannah natural-reserve site (southwest of Burkina Faso), the N_2O emission rate was 0.52 and 0.67 kg N ha^{-1} y^{-1} in 2005 and 2006, respectively. For Zimbabwean savannah, the measured N_2O flux was 0.25–0.5 kg N ha^{-1} y^{-1} (Rees et al., 2006). In China, there are no real savannahs as found in Africa, and the most similar vegetation type is Chinese tropical/subtropical grassland. Our estimate for these grasslands was 0.39 kg N ha^{-1} y^{-1}, within the range of values reported in Africa.

3.7.4 Global comparison

Prentice et al. (1993) estimated that the present total area of global grassland is 4.16 billion ha, and China has 8% of this. If we apply the modelled average N_2O emission rate (0.22 kg N ha^{-1} y^{-1}) based on this ratio, the global grassland N_2O emission would be 0.92 Tg N y^{-1}. Globally, the total anthropogenic emission of N_2O is estimated at 6.3–6.7 Tg N y^{-1} (Khalil and Rasmussen, 1992; IPCC, 2000). Of that, grassland accounts for 14% of annual total anthropogenic N_2O–N emission. This may underestimate the grassland N_2O emission contribution to the atmosphere, as most grasslands in China have relatively low emission rates compared to semi-natural grasslands.

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In China, grassland has a long history of anthropogenic use, and is currently experiencing serious degradation. Moderating the degradation and improving the grassland conditions are urgent tasks for sustainable development in China. New policies have been proposed to encourage farmers and herdsmen to maintain high productivity of grassland by converting farmland to grasslands or adopting grassland–farming rotations system (Nan, 2005). Specifically, intensive management practices have been advocated, which can improve the grassland and increase carbon sequestration (Conant et al., 2001), including fertilizer application and mowing (Committee on Scholarly Communication with the People's Republic of China and National Research Council 1992). However, such practices can also change the N_2O flux. More research is needed to determine optimal management strategies that achieve a balance between N_2O emission and carbon-sequestration. The present study was an attempt to apply process-based models such as DNDC for assessing N_2O inventory and mitigation potentials at a national scale.

4 Conclusions

The N_2O emissions from various grassland types in China differed. The emissions from temperate, montane, and tropical/subtropical grasslands were 0.23, 0.11 and 0.39 kg N ha^{-1} y^{-1}, respectively. Of the 337 million ha of grasslands nationwide in China, annual N_2O emissions were 76.5 Gg N. The N_2O emissions from the entire grassland ecosystem varied year-by-year and have increased constantly from 2000–2007, with climate change playing the main role in this process. Grasslands in China have been intensively developed recently, thus future emission estimates from grasslands may need to include more specific grassland management practices, land use change and spatially distributed grazing rates such as fertilizer application rates.

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Table 1. DNDC model results compared with the literature data.

Longitude	Latitude	Reference	N_2O	Modelled results ($kg\,N\,ha^{-1}\,y^{-1}$)	Location	Grassland Type
123.01–119.15	44.01–43.03	Huang et al. (2003)	0.72	0.70	Songnen Plain, China	Temperate Grassland
116–117	43–44	Du et al. (1997)	0.28	0.45	Inner Mongolia, China	Temperate Grassland
116–117	43.5–44	Dong et al. (2000)	0.56	0.45	Inner Mongolia, China	Temperate Grassland
116.7	43.62	Xu et al. (2003)	0.18	0.37	Inner Mongolia, China	Temperate Grassland
93.83	35.22	Pei et al. (2003, 2004)	0.05	0.06	Qinghai, China	Montane Grassland
115.5–117.2	43.5–44.6	Wang et al. (2003)	0.09	0.40	Inner Mongolia, China	Temperate Grassland
116.66	43.5	Du et al. (2006)	0.73	0.64	Inner Mongolia, China	Temperate Grassland
101.25	37.5	Du et al. (2008)	2.08	0.16	Qinghai, China	Montane Grassland
116.66	43.5	Chen et al. (2000)	0.17	0.40	Inner Mongolia, China	Temperate Grassland
a		Mummey et al. (2002)	0.28	0.22	US	Temperate Grassland
a		Mosier et al. (1993)	0.17	0.16	Wyoming, US	Montane grasslands

[a] For China domestic, the value extracted according to the coordinate of literature data, and for the other places of the world, the compared value was use the average value of similar grassland type in China. If the literature study area was smaller than the DNDC simulation unit, then the average literature value was applied.

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Table 2. Baseline values for sensitivity tests.

Property	Baseline value
Annual mean temperature (°C)	9
Total annual precipitation (mm)	520
Clay fraction (%)	0.19
Field capacity (%)	0.49
Wilting point (%)	0.22
Porosity (%)	0.451
Initial soil C fraction (kg C/kg soil)	0.0025
Bulk density (g/cm^3)	1.22
Soil pH	7.4
Number of days grazed (per year)	12
Grazing hours per day	12
Cattle grazing intensity (head/ha)	0.3
Sheep grazing intensity (head/ha)	3

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Table 3. Modelled annual N_2O emission rates for 18 types of grassland in China (kg N ha^{-1} y^{-1}), grassland area and total N_2O emission per year.

Grassland Type	Emission rates (kg N ha^{-1} y^{-1})	Grassland Area (million ha)	Total N_2O emission (Gg N y^{-1})
Temperate Meadow Steppe (TMS)	0.26	18	4.7
Temperate Steppe (TS)	0.33	47	15.5
Temperate Desert Steppe (TDS)	0.16	16	2.6
Alpine Meadow Steppe (AMS)	0.10	5	0.5
Alpine Steppe (AS)	0.08	30	2.4
Alpine Desert Steppe (ADS)	0.03	6	0.2
Temperate Steppe Desert (TSD)	0.11	7	0.8
Temperate Desert (TD)	0.09	20	1.8
Alpine Desert (AD)	0.03	5	0.2
Warm Temperate Tussock (WTT)	0.28	11	3.1
Warm Temperate Shrub Tussock (WTST)	0.30	12	3.6
Tropical Tussock (TT)	0.37	19	7
Tropical Shrub Tussock (TST)	0.37	17	6.3
Dry Tropical Shrub Tussock with Savanna (DTSTS)	0.32	1	0.3
Lowland Meadow (LM)	0.32	35	11.2
Mountain Meadow (MM)	0.23	22	5.1
Alpine Meadow (AM)	0.16	64	10.2
Swamp	0.48	2	1
Average rate/Total area/Total emission	0.22	337	76.5

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Table 4. Grassland categories, zonal climate and average N_2O flux.

Categories	Grassland Type	Annual Precipitation (mm)	Annual Temperature (°C)	Area (million ha) [%]	N_2O Emission Rate (kg N ha^{-1} $year^{-1}$)	Total N_2O Emission (Gg N y^{-1}) [%]
Temperate Grassland	TMS TS TDS TSD TD WTT WTST LM	282.11	5.54	165.92 [49]	0.23	43.3 [57]
Montane grasslands	AMS AS ADS AD AM MM	400.77	−1.25	132.56 [39]	0.11	18.6 [24]
Tropical/ subtropical grasslands	TT TST DTSTS Swamp	1109.49	16.22	39.50 [12]	0.39	14.6 [19]

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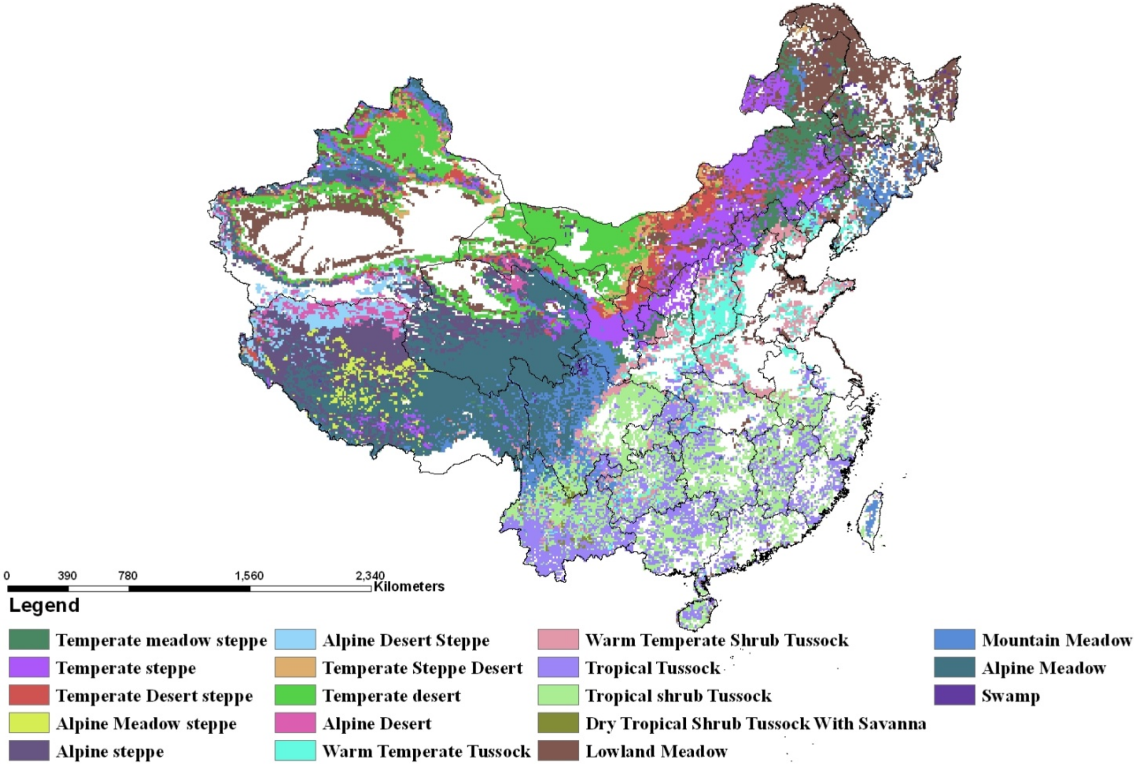

Fig. 1. China's 18 types grassland distributions.

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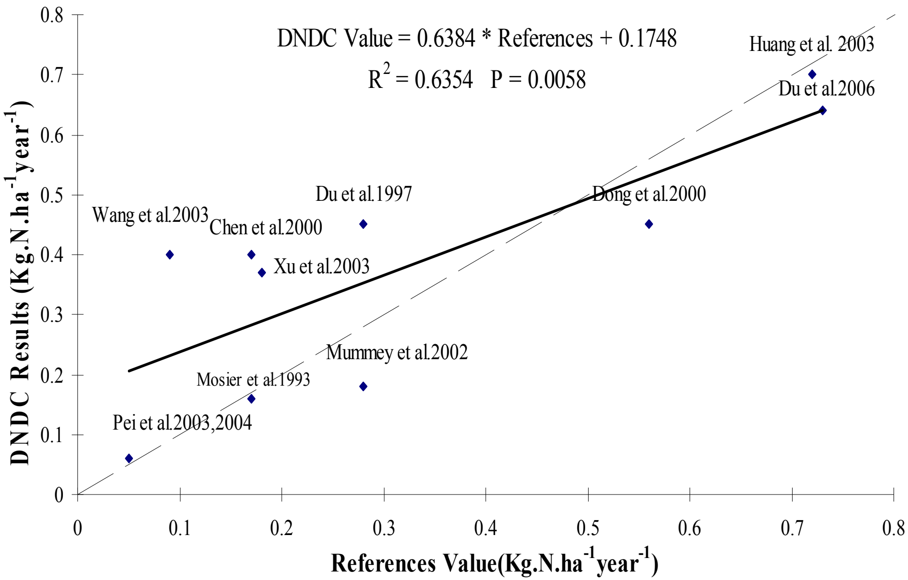

Fig. 2. DNDC results compared with literature reports. Dashed line is 1:1 line (Du et al., 2008 was excluded).

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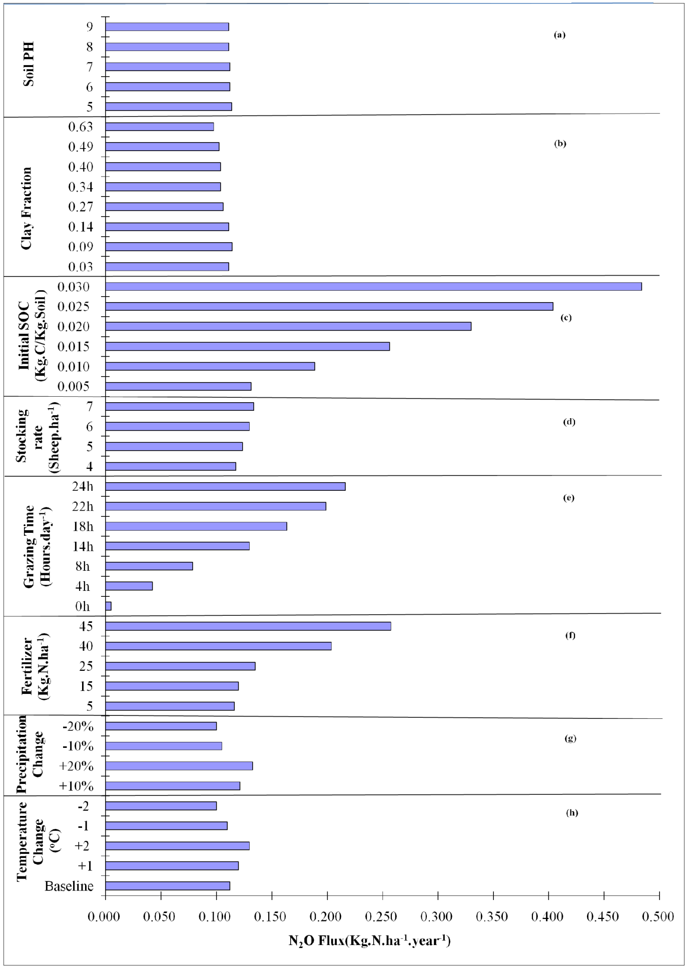

Fig. 3. Effect of changing a single factor of soil, management and climate on sensitive analysis scenario.

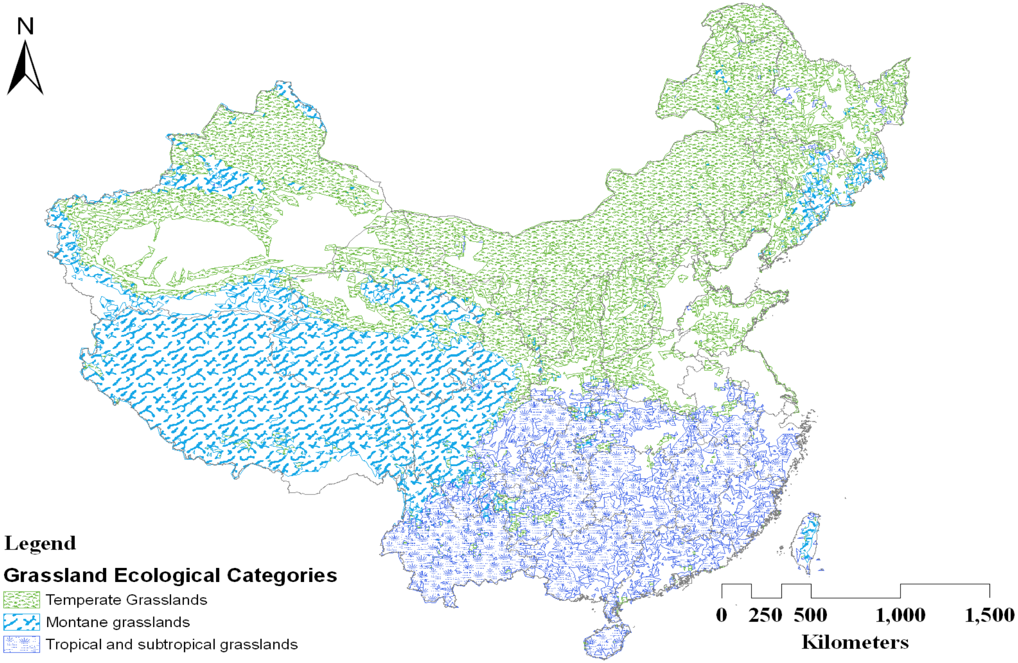

Fig. 4. Three grassland ecological categories of Chinese grasslands.

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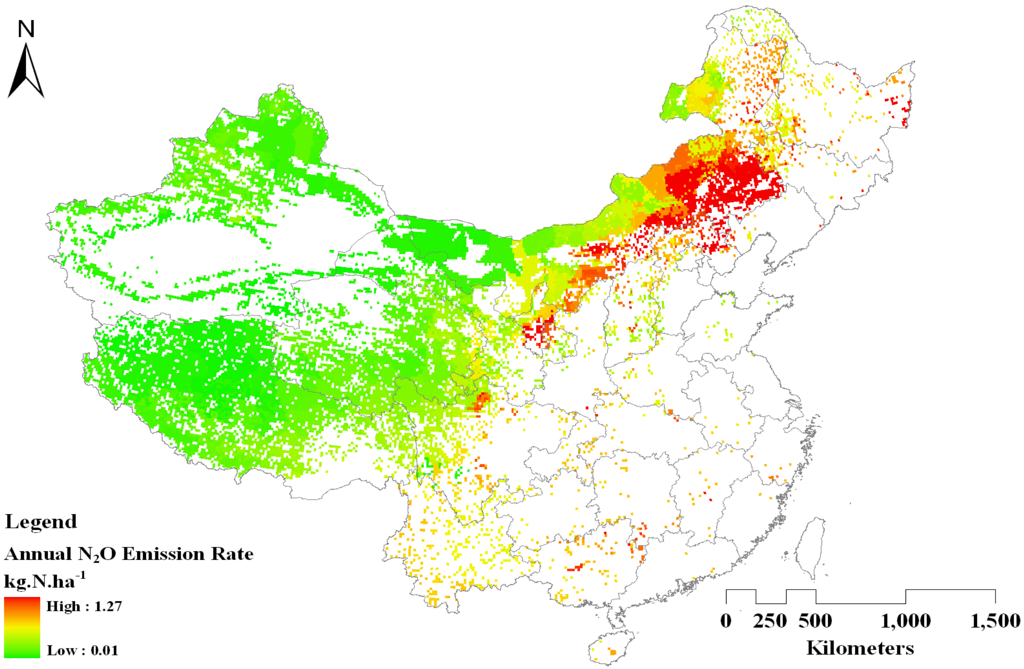

Fig. 5. The spatial distribution of N_2O flux for Chinese grassland (the blank area is non-grassland).

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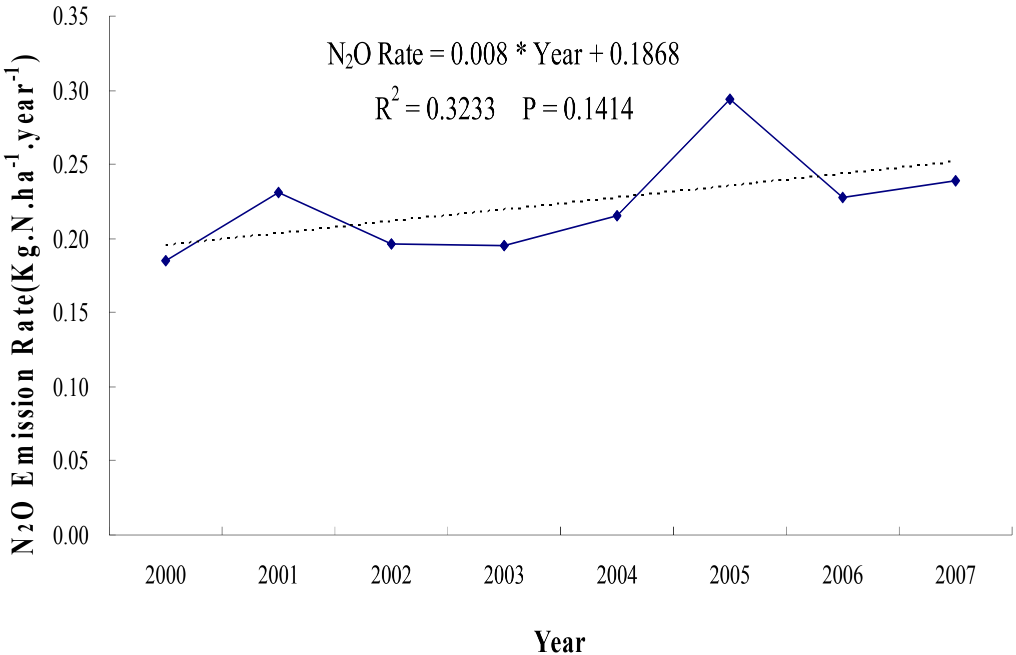

Fig. 6. Chinese grassland N_2O emission rate yearly changes for 2000–2007.

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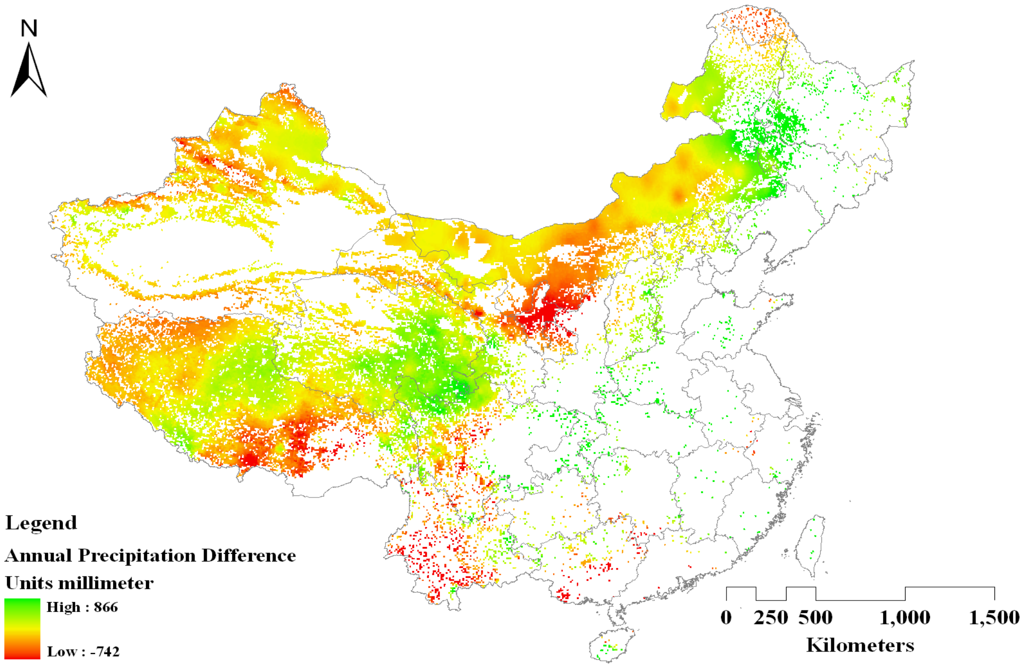

Fig. 7a. The annual accumulated precipitation difference between 2005 and 2001. Positive values indicate precipitation increased from 2001 to 2005, and negative values indicate a decrease.

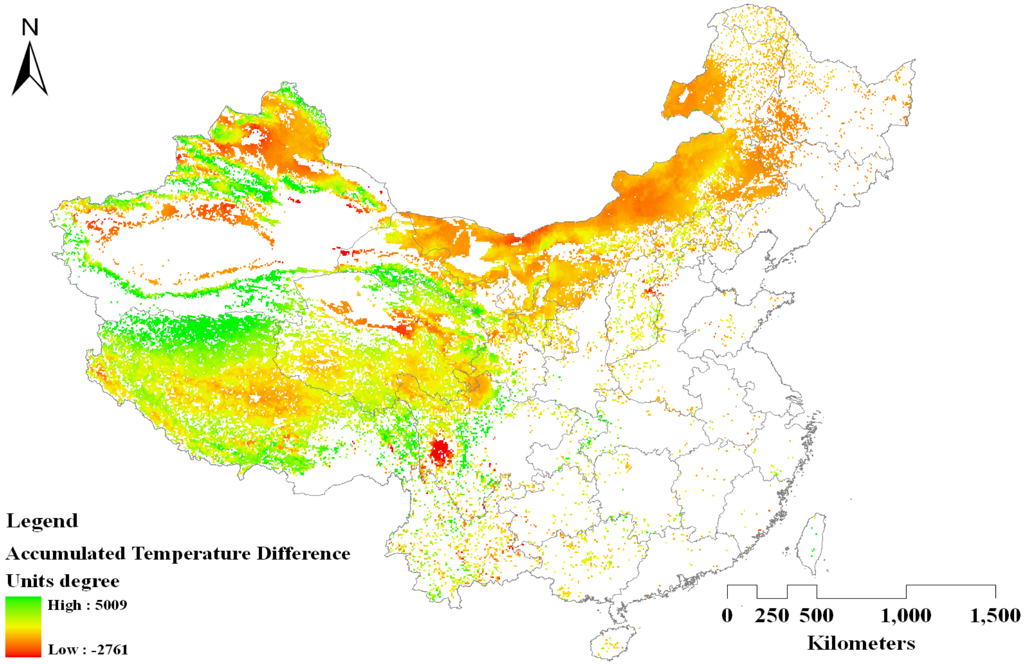

Fig. 7b. The accumulated temperature > 0 °C difference between 2005 and 2001. Positive values indicate accumulated temperature increased from 2001 to 2005, and negative values indicate a decrease.