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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 a regional or national level in China relies on the emission factor method, which is based on limited measurements. To improve the accuracy of the inventory by capturing the spatial variability of N_2O emissions under the diverse climate, soil and management conditions across China, we adopted an approach by utilizing a process-based biogeochemical model, DeNitrification-DeComposition (DNDC), to quantify N_2O emissions from Chinese grasslands. In the present study, DNDC was tested against datasets of N_2O fluxes measured at eight grassland sites in China with encouraging results. The validated DNDC was then linked to a GIS database holding spatially differentiated information of climate, soil, vegetation and management at county-level for all the grasslands in the country. Daily weather data for 2000–2007 from 670 meteorological stations across the entire domain were employed to serve the simulations. The modelled results on a national scale showed a clear geographic pattern of N_2O emissions. A high-emission strip showed up stretching from northeast to central China, which is consistent with the eastern boundary between the temperate grassland region and the major agricultural regions of China. The grasslands in the western mountain regions, however, emitted much less N_2O. The regionally averaged rates of N_2O emissions were 0.26, 0.14 and 0.38 kg nitrogen (N) $ha^{-1}\,y^{-1}$ for the temperate, montane and tropical/subtropical grasslands, respectively. The annual mean N_2O emission from the total 337 million ha of grasslands in China was 76.5 ± 12.8 Gg N for the simulated years.

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the global average surface temperature has increased by around $0.74 \pm 0.18\,^{\circ}$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). The increased GHG emissions have altered the energy balance of the climate system (IPCC, 2007). On a global scale, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), contribute 76.7, 14.3 and 7.9%, respectively, to the anthropogenic GHGs' effect (IPCC, 2007). The instantaneous flux rates of the GHGs were an important clue for assessing the terrestrial ecosystem contributions to climate change (Du et al., 2008). Among the three GHGs, N_2O possesses the longest atmospheric lifetime and highest radiative forcing potential (Cicerone, 1989; Mummey et al., 2000; IPCC, 2007). However, due to the difficulties in monitoring the gas fluxes at a regional scale, large uncertainty exists on 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, there have been

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fewer studies on 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 a 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 used to estimate N_2O emissions on a national scale in Initial National Communication on Climate Change by the People's Republic of China in 2004. However, it is less capable of quantifying impacts of climate or the management of the gas fluxes. Consequently process-oriented models were proposed to improve N_2O emission estimates (Boeckx and Van Cleemput, 2001). On a national scale, process-based models have proven useful in reducing uncertainty and helping to understand the complex biogeochemical processes involved in trace gas production (Barnsley, 2007). The Chinese government reported agricultural N_2O emissions in the 1990s using IPCC methods, but cited a deficit of emissions data specific to grasslands in the report (China, 2004). Li et al. (2001) compared the IPCC method and the DNDC model in the evaluation of Chinese agricultural N_2O emissions and found that the process-based DNDC model and the strictly empirical IPCC methodology gave similar estimates of direct N_2O emissions from cropland soils in 1990. However, DNDC provided the spatial pattern of N_2O emissions on a national scale (Li et al., 2001).

Grassland is widely distributed in north and northwest China (Kang et al., 2007), and is under threat of serious degradation and over grazing. Researchers have advocated alternative grassland management practices including intensive management (Nan, 2005). Grassland management practices have recently undergone some significant changes in China due to the economic development over the past decades (Chen and Chen, 2007). To slow down the degradation to maintain sustainability of the grasslands, regulations with new management practices have been introduced by the Chinese central government (Chen and Chen, 2007; Unkovich and Nan, 2008). These include converting reclaimed land to pasture lands, practicing rotational grazing methods using fencing; promoting conservation practices; tending and controlling rodents and insect pests; promoting rangeland improvements such as shallow-ploughing, fertilization and irrigation; and promoting restoration by aerial-sowing, cultivation practices, converting cultivated lands to pastures, and the establishment of a forage base (Yang, 1992; Chen and Chen, 2007). Among of these practices, fertilization and improved grazing management practices are highly recommended (Conant et al., 2001). These management options potentially alter N_2O emissions and, hence, change the national inventory of N_2O. Some preliminary researches indicated that the magnitudes of N_2O fluxes from Chinese grassland vary greatly in space and time (Du et al., 1997, 2006; Dong et al., 2000; Xu et al., 2003). There is a need to use process-based models to achieve a more accurate estimate of the N_2O emissions on a national level in consideration of the dynamics of grassland management. This paper reports the first attempt to quantify N_2O emissions from Chinese grasslands with a process-based model. To approach this goal, we adopted a four-phase method that included (1) database development, (2) scaling up, (3) model validation, and (4) sensitivity analysis.

2 Method

2.1 Database development

To apply DNDC on 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 km^2. The database consisted of: (1) 18 grassland types with plant properties (e.g. maximal production, maximal height, and root/shoot ratio); (2) soil properties (e.g. maximum and minimum soil organic carbon(SOC) 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 into 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 and the database had 10 km-resolution (Fig. 1).

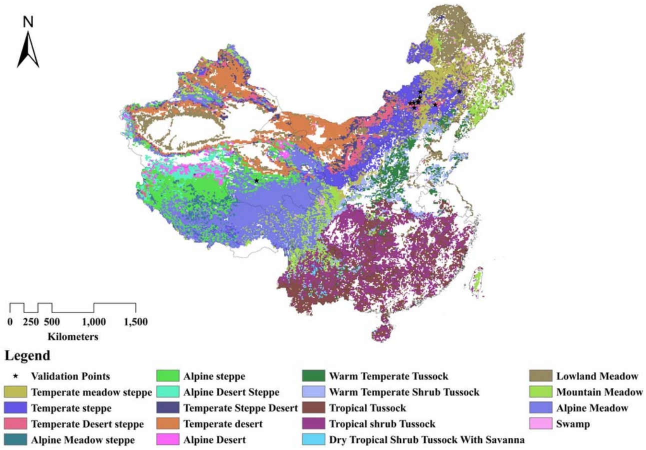

Fig. 1. China's 18 types grassland distributions, five-pointed stars are model validation points.

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 (National Soil Survey Office, 1993, 1994a, b, 1995a, b, 1996). 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 proportions) and spatial information (Shi et al., 2004; Yu et al., 2007), which were used in model simulation. In this study, we used data in the upper 0–10-cm soil profile as the soil surface properties for model simulations and for data assimilation; it was resampled to 10 km-resolution.

2.1.3 Climate dataset

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

2.1.4 Grazing data

There are deficiencies in the county-scale statistical data for grazing stock and great heterogeneity in the grassland management regimes in China. Based on the statistical data of 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 that livestock were 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^{-1} 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 (Fig. 3c), 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).

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, redox potential 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 also been 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. Eight grassland sites use the same management practices as in the DNDC simulation, where N_2O fluxes were measured and the annual emission rates were reported in publications (Fig. 1) were used for validation tests. The sites were natural grasslands as defined by Coupland (1992) without any fertilizer and grazing applied. The modelled non-grazing annual N_2O emissions rates were consistent with reports for the sites (Fig. 2), Regression analysis demonstrated that the simulated emissions explained 64% of the variation in observed emissions. The intercept is significantly different from 0 at the 0.05 alpha level. For all experiments presented in Table 1, the RMSE is equal to 0.87 kg N ha^{-1} year^{-1}, the EF is positive, and CD is greater than 1 (Table 1).

Table 1. Selected statistics for comparison of observed and simulated N_2O emissions (kg N ha^{-1} year^{-1}).

Data source	RMSE	EF	CD
References points	0.87	0.75	3.97

RMSE: the root mean squared error; EF: the coefficient of model efficiency; CD: the coefficient of model determination (Smith et al., 1997)

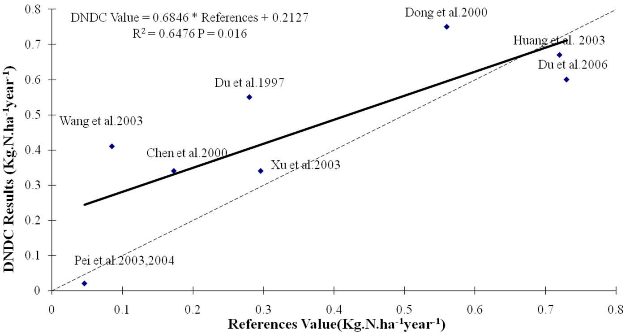

Fig. 2. DNDC results compared with literature reports. Dashed line is 1:1 line.

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 SOC 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 is the basis where the model can be used to assess how climate change and human management practices affect N_2O emissions from the vast grasslands in China.

Sensitivity to soil attributes

The modelled N_2O emission rates correlated well with the initial SOC contents (Fig. 3c), that is in agreement with the observations made by other researchers (e.g., Babu et al., 2006). Variation of the initial SOC content showed significant effects on production and emission of N_2O. More N_2O was produced from soils with pH 7 than from alkaline soils (Fig. 3a), however, pH had a minor effect on N_2O emissions. Soil texture was also a sensitive factor due to its effects on soil aeration status; sandy loam soil was more likely to produce higher N_2O than clay soil (Fig. 3b).

Table 2. Baseline values for sensitivity tests.

Property	Baseline value	Range tested
Annual mean temperature (°C)	9	7–11
Total annual precipitation (mm)	520	416–624
Clay fraction (%)	0.19	0.03–0.63
Field capacity (%)	0.49	Not varied
Wilting point (%)	0.22	Not varied
Porosity (%)	0.451	Not varied
Initial soil C fraction (kg C kg^{-1} soil)	0.0025	0.005–0.03
Bulk density (g cm^{-3})	1.22	Not varied
Soil pH	7.4	5–9
Number of days grazed (y^{-1})	12	Not varied
Grazing hours per day	12	0–24
Cattle grazing intensity (head ha^{-1})	0.3	Not varied
Sheep grazing intensity (head ha^{-1})	3	4–7
Fertilizer(Kg N ha^{-1})	0	5–45

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} y^{-1}, N_2O emissions increased from 0.1 to 0.25 kg N ha^{-1} y^{-1} (Fig. 3f). This suggested that the fertilized grassland could increase N_2O emission greatly.

Sensitivity to climate conditions

The N_2O emissions were susceptible to changes in rainfall and temperature, which is in agreement with previous studies that show that N_2O emissions were positively correlated with air or soil temperature (Yamulki et al., 1997; Dong et al., 2000). In the present 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 in DNDC. Denitrification occurs under anaerobic conditions in soils with high moisture content, so we would expect N_2O emissions to increase with precipitation. The effect of temperature was examined by running a sequence of simulations with daily temperatures varied by a 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 changed

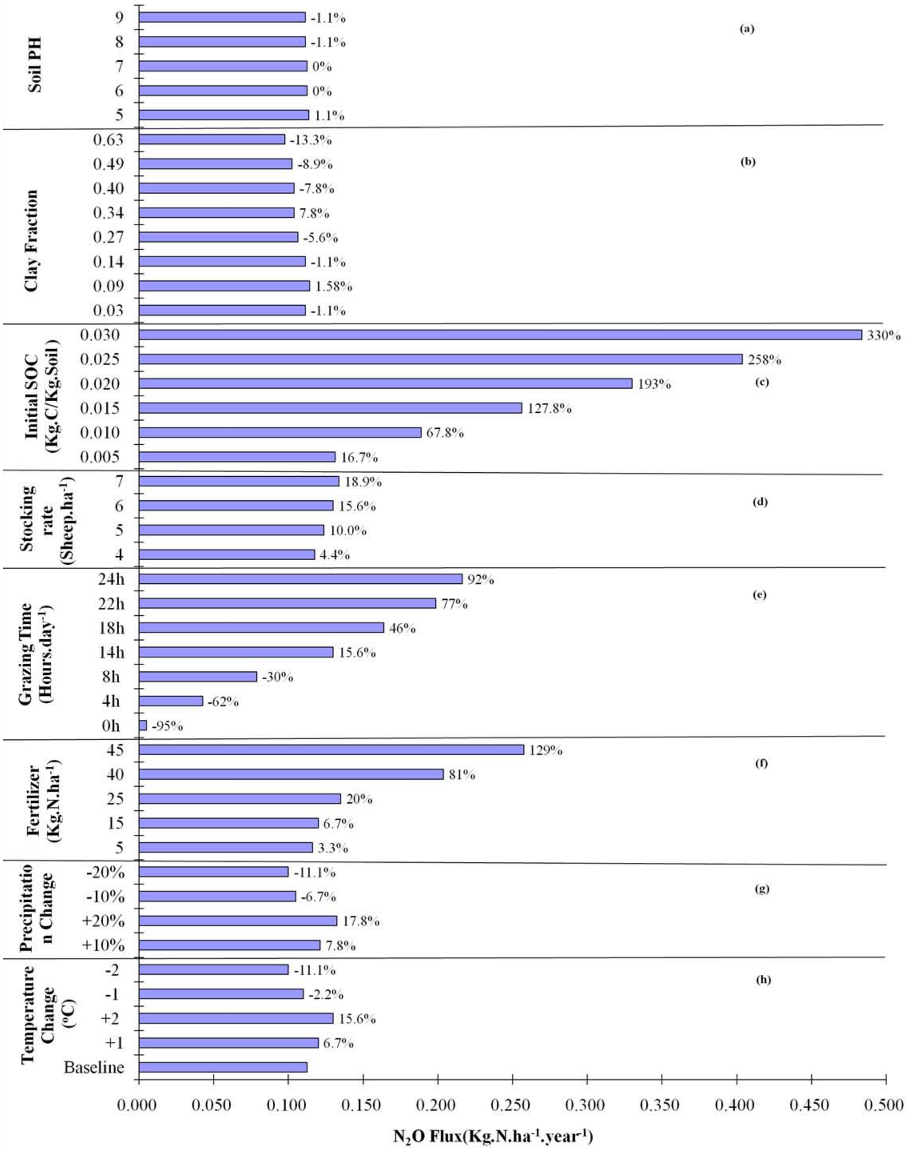

Fig. 3. Effect of changing a single factor of soil, management and climate on sensitivity analysis scenario.

slightly; but when the increase was 2 °C, the total N_2O emissions changed significantly (Fig. 3h). When temperature decreased, N_2O emissions also clearly decreased, 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).

3.2 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 $< 0.5\,\mathrm{kg\,N\,ha^{-1}\,y^{-1}}$ with the highest for swamp grassland and the lowest for Alpine desert grassland (0.48 and $0.02\,\mathrm{kg\,N\,ha^{-1}\,y^{-1}}$, respectively) and the national average $0.22\,\mathrm{kg\,N\,ha^{-1}\,y^{-1}}$. 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 $76.5 \pm 12.8\,\mathrm{Gg\,N_2O\text{-}N\,y^{-1}}$ on a multi-year average basis.

The modelled N_2O fluxes were analysed by combining the 18 types of grassland into three categories based on ecological climate zones (China Meteorological Administration, 2002). The three categories were temperate, montane and tropical/subtropical grasslands (Table 4, Fig. 4). Each of the three categories possessed specific environmental features and was basically consistent with climate patterns. The

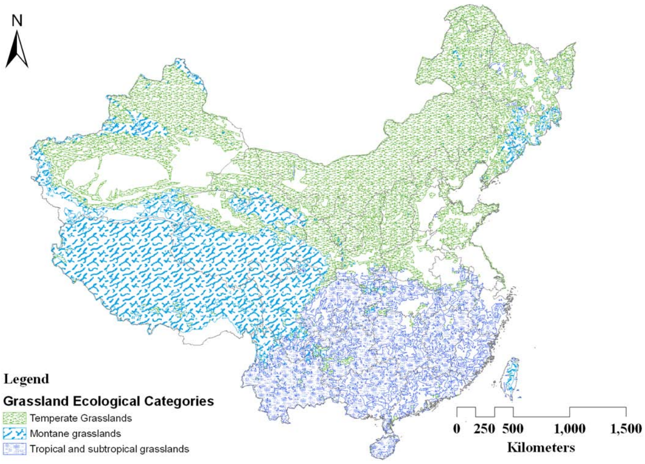

Fig. 4. Three grassland ecological categories of Chinese grasslands.

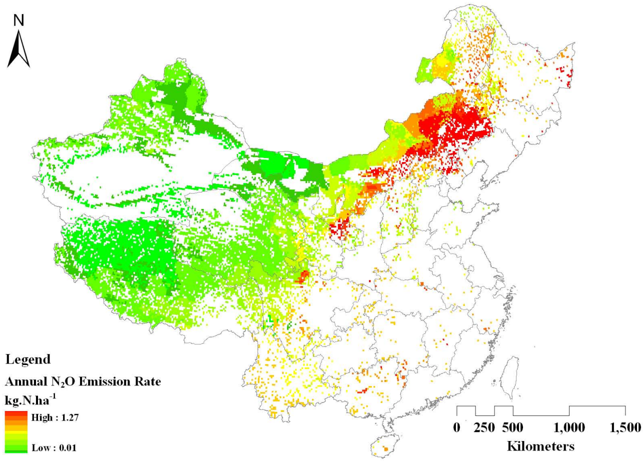

Fig. 5. The spatial distribution of N_2O flux for Chinese grassland (the blank area is non-grassland).

greatest N_2O flux (0.38 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 0.14 kg N ha^{-1} y^{-1}; this region is humid but with low temperature. The temperate grassland region had a medium emission flux, averaging 0.26 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 the 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.

3.3 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 east to west 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, but not significantly (P=0.14) (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. From 2000–2007, climate is the only changed factor in the simulation. 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 reason for varied N_2O emissions. In the northern grassland region, the precipitation and the temperature increased (Fig. 7a, b), which is believed to have caused the N_2O emissions change. As climate could play an important role in N_2O emissions, further climate change may have some impact on the N_2O emission pattern. However, more quantified research and long time-scale simulation is needed to verify the relationship between climate and N_2O emissions.

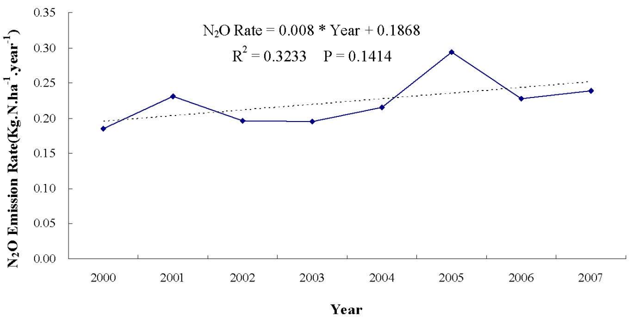

Fig. 6. Chinese grassland N_2O emission rate yearly changes for 2000–2007.

3.4 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 can 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

Table 3. Modelled average N_2O emission rates over eight years 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–1y–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 ± 12.8

Table 4. Grassland categories, zonal climate and average N_2O flux. The weighted emission rates were calculated by category total emission 736 divided by category total area.

Categories	Grassland Type	Annual Precipitation (mm)	Annual Temperature (°C)	Area (million ha) [%]	Weighted N_2O Emission Rate ($kg\,N\,ha^{-1}\,y^{-1}$)	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]	0.26	43.3 [57]
Montane grasslands	AMS AS ADS AD AM MM	400.77	−1.25	132.56 [39]	0.14	18.6 [24]
Tropical/ subtropical grasslands	TT TST DTSTS Swamp	1109.49	16.22	39.50 [12]	0.38	14.6 [19]

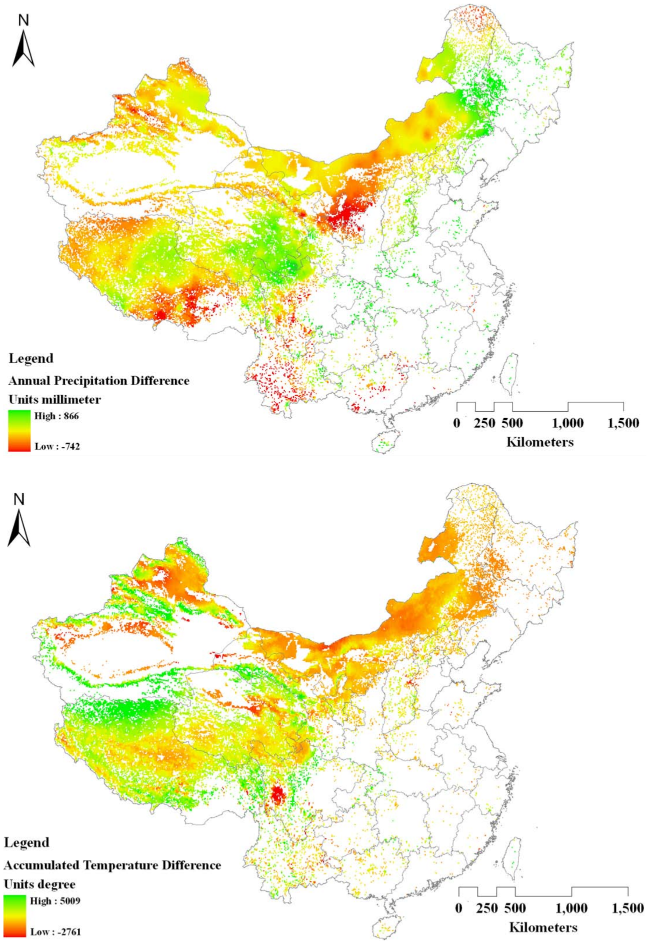

Fig. 7. (a) The annual accumulated precipitation difference between 2005 and 2001. Positive values indicate precipitation increased between 2001 to 2005, and negative values indicate a decrease, **(b)** The accumulated temperature $> 0\,^{\circ}\mathrm{C}$ difference between 2005 and 2001. Positive values indicate accumulated temperature increased between 2001 to 2005, and negative values indicate a decrease.

modelled N_2O fluxes were relatively high in these areas. As part of the United Nations Framework Convention on Climate Change, the Chinese Government provided a 1994 national greenhouse gas inventory (China P. R. C., 2004), which was estimated using the IPCC method tier 1. However, it did not report the direct N_2O emission from grassland and took only the direct N_2O emissions from cropland (474 Gg N_2O-N) into account. Our estimated grassland N_2O emission was roughly 1/6 of the N_2O emission of cropland reported by China P. R. C. (2004) throughout the country. Thus, in the future national N_2O inventory, the grassland direct N_2O emissions should be taken into account. Therefore, our work should be a good complement to the national N_2O inventory. To estimate the reliability of our modelled results and provide readers with a worldwide ranking of Chinese grassland N_2O emissions, we compared our modelled N_2O fluxes with those reported for other parts of the world, based on similar grassland types.

3.4.1 Comparison with North American grasslands

The temperate grassland in Inner Mongolia is similar to the North Great Plains grassland in the USA. The two grasslands are located at similar latitudes. Mummey et al. (2000) reported 0.24 kg N ha^{-1} y^{-1} emitted from the 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 0.26 kg N ha^{-1} y^{-1} for temperate grassland in China. For the subalpine meadow experiment site in the USA, 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 0.14 kg N ha^{-1} y^{-1}. The comparisons indicate that the DNDC estimated values were within reasonable ranges.

3.4.2 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 0.26 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 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}) similar to that of 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). However, in China, grasslands are sparsely fertilized or irrigated (Huang et al., 2003; Nan, 2005; Unkovich and Nan, 2008).

3.4.3 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 0.38 kg N ha^{-1} y^{-1}, within the range of values reported in Africa.

3.4.4 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.

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 rotation systems (Nan, 2005). Specifically, intensive management practices have been advocated, which can improve the grassland and increase carbon sequestration (Conant et al., 2001), and include 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 the DNDC for assessing N_2O inventory and mitigation potentials on a national scale.

3.5 Uncertainty analysis

Great efforts were made in this study to reduce the uncertainties in the estimation of N_2O inventory, especially in the input data. All input datasets are taken from official statistical data of China and the national survey in order to simulate as precisely as possible. However, there are still uncertainties associated with the climate data, grazing regime and soil data.

Climate is a key parameter of the DNDC model (Fig. 3). In this research, we interpolated precipitation, which produced a larger number of rainfall events with less rainfall per event, but the total precipitation was similar to the observed value. Although there were no significant differences in N_2O emission between interpolated precipitation and observed precipitation, interpolated data is still a potential source of uncertainty in simulated results (supplement Figs. 1, 2 and 3). In the Qinghai-Tibet plateau, the meteorological stations are very scarce (supplement Fig. 4) and, therefore, the interpolated temperature could be higher than the real value. Higher temperature can increase N_2O emissions (Fig. 3h), and so cause overestimation of the total N_2O emissions.

In Chinese natural grassland regions, a rotation grazing method is usually adopted, which requires transferring livestock from one pasture to another in different seasons and staying in the same pasture for the whole season. For example, in the Qinghai-Tibet grassland region, there are three types of pastures: spring-winter, summer, and autumn pasture. In reality, every pasture will be grazed in turn according to the seasons. This grassland management, however, was simplified in this research as we could not find any specific statistical data concerning it. We assumed that livestock stayed in the same pasture for the whole year with 12 h d^{-1} of grazing and at stocking rates that were the same throughout the country. Furthermore, we assumed all grasslands were useable. These assumptions could induce uncertainties in the simulation results. The average stocking density rate may be underestimated, since not all grasslands are usable or are grazed at the same time. This simplified grazing assumption may underestimate N_2O emissions (Fig. 3d, e). Accurate soil properties can help to reduce uncertainties. In this research, we used the second national soil survey data conducted during 1979–1994 as the initial model input values; it is likely that these values have changed since then. Soil properties were one of the most sensitive factors (Fig. 3b, c), and outdated soil values will increase the uncertainties. Chinese grassland soil is C-neutral and the SOC has increased slightly in the last two decades (Yang et al., 2010), however, this slight SOC increase could cause underestimation of true N_2O emissions.

4 Conclusions

The N_2O emission rates from various grassland types in China differed. The emissions from temperate, montane, and tropical/subtropical grasslands were 0.26, 0.14 and 0.38 kg N ha^{-1} y^{-1}, respectively. Of the 337 million ha of grasslands in China, the annual N_2O emission was 76.5 ± 12.8 Gg N. The N_2O emissions from the entire grassland ecosystems varied year-by-year and increased during 2000–2007, with climate change playing an important role in this process. Grasslands in China have recently been intensively developed and, thus, future emission estimates from grasslands may need to account for more specific grassland management practices, land use change, spatially distributed grazing rates and fertilizer application rates.

Supplementary material related to this article is available online at:
http://www.biogeosciences.net/7/2039/2010/bg-7-2039-2010-supplement.pdf.

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