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Yangong DU[1, 2], Xiaoyong CUI[2]*, Guangmin CAO[3], Xudong ZHAO[3], Guixia YANG[1]

[1] Key Laboratory of Resources Remote Sensing and Digital Agriculture, Ministry of Agriculture, Beijing, 100081, China
[2] College of Resource and Environment, Graduate University of the Chinese Academy of Sciences, 19 Yuquan Road, Beijing, 100039, China
[3] Northwest Institute of Plateau Biology, The Chinese Academy of Sciences, Xiguan Street, Xining, Qinghai P.R, 810001, China
*e-mail: cuixy@gucas.ac.cn (*corresponding author*)

SIMULATING N_2O EMISSION FROM *KOBRESIA HUMILIS* SERG. ALPINE MEADOW ON TIBETAN PLATEAU WITH THE DNDC MODEL

ABSTRACT: Field measured N_2O emissions in two years were used to parameterize and validate a process-based model, DNDC, for an alpine *Kobresia humilis* meadow on the Tibetan Plateau in China. Although this model failed to capture the N_2O fluxes in some time periods in the spring or autumn, the modeled results showed overall a good performance in terms of simulating the seasonal variation of N_2O fluxes and quantifying the annual total emissions. The relative deviation on the annual basis was about 12.4% and –15.9% for the two years, respectively. The modeled data showed that nitrification contributed about 53% of total N_2O production, slightly higher than denitrification. The modeled fluxes were sensitive to soil organic content (SOC), pH, and temperature, but less sensitive to variation of precipitation, soil ammonium and nitrate contents. Further modifications for the model were suggested to focus on the process of soil freezing and thawing as well as the crop growth sub-model that would improve the model's performance for quantifying N_2O emission from the alpine meadow.

KEY WORDS**:** DNDC model, N_2O emission, nitrification, alpine meadow

1. INTRODUCTION

N_2O was one of the major long live greenhouse gases with much higher radiative forcing than CO_2 per molecular weight (IPCC 2007). Recent systematic measurement of atmosphere N_2O indicated a concentration level of approximate 319 ppbv, with an increasing trend of 0.8% per year (World Meteorological Organization 2006, IPCC 2007). N_2O was dominantly produced from nitrification and denitrification in agriculture and grassland soils (Arah *et al.* 1991, Bouwman 1996, Bouwman *et al.* 2002, Bhandral *et al.* 2007). However, the contribution and controls of each process were still unclear (Shaw *et al.* 2006, Giltrap *et al.* 2008), though a few factors had been shown to affect N_2O production and emission, such as nitrogen (nitrate and ammonium) availability and factors influencing soil redox potential, i.e. soil moisture and temperature (Carran and Theobald 1995, Clayton *et al.* 1997, Dobbie and Smith 2001), soil texture, pH and organic matter content (Wrage *et al.* 2001, Xu *et al.* 2003a, Holst *et al.* 2007).

Few long-term field measurements were available to characterize the year-round variation of N_2O production and emission (Saggar *et al.* 2004). Most estimates of annual N_2O emission were calculated by extrapolating average fluxes from a few sites in an ecosystem only in growing seasons (Wolf *et al.* 2010). IPCC used a default value of 1.25% loss of the applied N as N_2O emission for national inventory (Schils *et al.* 2008). This uniform value, however, departed from many ecosystems of the world (Williams *et al.* 1999, Huth *et al.* 2010). There was still considerable uncertainty in global N_2O budget due to the high variability (Pihlatie *et al.* 2005). It was urgent to have spatially and temporally explicit data on N_2O fluxes from soils of grassland soils for better estimation of regional and national greenhouse gas inventories (Saggar *et al.* 2007, Lin *et al.* 2009).

Modeling was proved to be able to play a role in assessments of long term regional greenhouse gases fluxes (Farquharson and Baldock 2008). Process-oriented models were testified as an option for constructing greenhouse gas inventories (Giltrap *et al.* 2008). The DNDC model was a process-based model. It had been widely tested and applied in both croplands and grasslands (Li 2000, Beheydt *et al.*, 2007, Tonitto *et al.* 2007) in many countries (Babu *et al.* 2006, Abdalla *et al.* 2009). It had also been successfully used to assess the effects of climate and mitigation strategies on N_2O emissions (Giltrap *et al.* 2008).

The Tibetan Plateau occupies about 25% of China's total territory. Alpine meadow is one of the dominant vegetations on the plateau (Wang *et al.* 2008, Du *et al.* 2010). Evidences showed that the ecosystems on the plateau were fragile and sensitive to undergoing climatic warming (Thompson *et al.* 2000). N transformation processes were also proved to be a key response to climate variation and grazing perturbations in the alpine meadows (Jonasson *et al.* 1993, Schmidt *et al.* 2002). Artificial warming experiments with precipitation manipulations had been carried out for almost a decade in the alpine meadow ecosystems on the plateau. However, N_2O emission measurements and modeling studies remained to be rare for the alpine meadows in China (Xu *et al.* 2003a).

In this study, we made use of N_2O emission data measured *in situ* for two years in an alpine meadow ecosystem on Tibetan Plateau (Du *et al.* 2008) to parameterize and validate the DNDC model. The validated model was then employed to identify the N_2O emissions from nitrification and denitrification, respectively in response to several environmental drivers. The objectives of the study reported in the paper were to investigate (1) the applicability of the DNDC model in simulating N_2O emission from the alpine meadow on the Tibetan Plateau; and (2) the sensitivity of N_2O emission to major environmental factors, especially the factors related to climate change.

2. STUDY SITE

The study site was located at Haibei Alpine Meadow Research Station (37°32'N, 101°15'E, 3280 m altitude), the Chinese Academy of Sciences. Annual precipitation averaged 560 mm in the past 20 years, of which 85% was concentrated in growing season from May to September (Li *et al.* 2004). Overall annual rainfall was 536 and 479 mm in the experimental periods in 2004 and 2005, respectively. Mean annual air temperature was −1.1 and −0.5°C for the two years. The soil is Mat-Gryic Cambisol (Chinese Soil Taxonomy Research Group 1995). It has high organic matter content (Du *et al.* 2008) other soil basic properties are presented in Table 1.

Kobresia humilis Serg. is one of the dominant alpine meadow types in the plateau. The community has more than 40 species per m^2 and consists of two vertical layers. The upper layer is dominated by *Festuca ovina* Linn., *F. rubra* Linn., *Stipa aliena* Keng., *Elymus nutans* Griseb., *Helictotrichon tibetica* Henr., *Koele-*

Table 1. Soil pH, organic carbon content and bulk density of the alpine *Kobresia humilis* meadow.

Soil depth (cm)	pH	Organic C (%)	Bulk density (g cm^{-3})
0–10	7.3±0.4	5.5	0.75±0.05
10–20	7.2±0.5	3.3	1.11±0.09
20–30	–	2.7	1.13±0.04
30–40	–	1.9	1.15±0.03

ria cristata Linn., and *Poa crymophila* Keng., and the lower layer by *K. humilis* Serg., *Saussurea superba* Anth., *Potentilla saundersiana* Royle., *Leontopodium nanum* Hand.-Mazz. and *Lancea tibetica* Hook. f. et Thoms. The experimental site was on a flat plain, where yaks and goats grazed from late September to the end of April since 1982. Vegetation coverage ranges from 75 to 80%. Bare soil resulted from serious degradation occupied about 2% of the total community area (Du *et al.* 2010).

3. METHODS

3.1. Treatment and N_2O flux measurement

In May 2003, three plots were setup in a *Kobresia humilis* meadow. Nitrous oxide (N_2O) emission was measured with static chamber method. In each plot a stainless steel pedestal was installed permanently. The lower edge of the pedestal reached 10 cm deep in the soil. The ground area in the pedestal was 0.5 × 0.5 m^2. Opaque plexiglas chamber with height of 50 cm was used for gas sampling. Each chamber was equipped with two electric fans to mix the air and a thermo-probe to monitor temperature in the chamber during measurements. To avoid too much increase of the air temperature in the chambers, they were covered with foam and white waterproof cloth.

Four air samples were taken from each chamber with plastic syringes every 10 min during sampling. The samples were analyzed by an improved gas chromatograph (HP4890D, Agilent Co.) system with electron capture detector (ECD). Injection/detection and column (stainless steel 3 m × 2 mm Porapak Q, Agilent Co.) oven temperature was 55°C and 330°C, respectively. Hourly N_2O emissions (μg N_2O m^{-2} h^{-1}) were calculated based on the slope of the linear increase in N_2O concentration over the sampling period, as follows:

$$Flux_{N_2O} = \rho \times \frac{V}{A} \times \frac{P}{P_0} \times \frac{T_0}{T} \times \frac{dC_t}{dt} \qquad (1)$$

$Flux_{\mathrm{N2O}}$ was hourly N_2O emission rate (μg N_2O m^{-2} h^{-1}). ρ was air density inside the chamber. C_t denoted N_2O concentration in the chamber at time t. V was the volume of the chamber. A was the ground area covered by the chamber. P_0 and T_0 were air pressure and temperature at standard state (1.103×10^5 Pa and 273 K, respectively). P and T were local air pressure and air temperature in the chambers.

3.2. Model parameterization and validation

Daily air temperature (maximum and minimum) and precipitation records were obtained from weather station at the Haibei Station. The other input parameters were achieved based on direct measurements or published data (Table 2, Cao *et al.* 2004, Du *et al.* 2007, Hu *et al.* 2008, Wang *et al.* 2008). Water filled pore space (WFPS) was calculated from soil gravimetric water content and bulk density (Wang *et al.* 2009). Soil aeration status is simulated by calculating oxygen diffusion and consumption in soil profiles, and then daily emissions of N_2O were computed

Table 2. Input parameters of DNDC model for the alpine *Kobresia humilis* meadow.

Item	Data
Latitude	37.53
N concentration in rainfall (mg N L^{-1})	1.34
Atmosphereric CO_2 concentrations (μL L^{-1})	350*
Vegetation type	perennial-grass*
Soil texture	loam
Bulk density (g cm^{-3})	0.75
Clay fraction	0.19
Soil pH	7.0
Soil organic carbon (kg C kg^{-1})	0.045
WFPS at field capacity	0.78
WFPS at wilting point	0.22
Slope	0 *

* default values from DNDC model

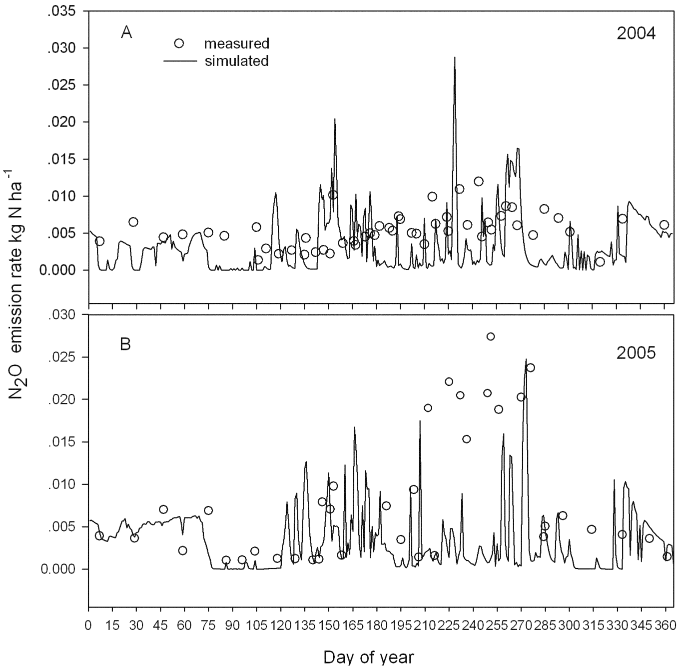

Fig. 1. Comparison of simulated *versus* measured N_2O flux from the *Kobresia humilis* alpine meadow in 2004 and 2005.

for both nitrification and denitrification (Li *et al.* 2000). In situ monitored N_2O emissions in 2004 were used to modify model parameters, and data measured in 2005 were used for model validation.

3.3. Statistical analysis

Linear regression analyses were adopted to examine the relationship between the measured and modeled monthly N_2O emissions. Independent sample T-test and linear regression analysis were performed to compare the modeled and mesured N_2O fluxes in SPSS$^{®}$ 16 (System Software Inc.).

4. RESULTS

4.1. Discrepancies between simulated and observed daily N_2O emission rates

The studied ecosystem was assumed at steady state, since it had been in current land-use pattern for more than 30 years. The comparison of simulated *versus* observed daily N_2O flux showed that the DNDC model fairly simulated the seasonal variation in 2004 and 2005. Some discrepancies between modeled and measured N_2O emission peaks during the summer time are expected because of the high spatial and temporal heterogeneity of the soil. The model obviously underestimated the flux during the spring and autumn period, especially in 2005 (Fig. 1), when soil WFPS was lower than field capacity and nitrification was the predominant source.

4.2. Modeled and measured monthly and yearly cumulative fluxes

There was dramatic temporal variation in the N_2O fluxes measured in the two years. High flux rates were generally observed from June to October (Fig. 2). The simulated monthly fluxes were mostly from 0.085 to 0.25 kg N ha^{-1} in 2004 and from 0.063 to 0.36 kg N ha^{-1} in 2005. In both years nitrification was the predominant process, contributing about 53.0 and 52.6% to the total N_2O emissions (Table 3). The simulated and measured values of monthly cumulative N_2O emission were closely correlated (Fig. 2, $P < 0.05$), and the regression models in the two years were significant correlated (Table 4).

Both simulated and measured annual fluxes in 2005 were higher than that in 2004.

Table 3. The flux of N_2O in alpine meadow and the difference between simulated and measured (kg N ha^{-1}).

Years	Simulated	Measured	Relative deviation (%)	T-test	Nitrification (%)
2004	2.26	2.01	12.4	$P > 0.05$	53.0
2005	2.49	2.96	−15.9		52.6

Table 4. The model of simulated and measured N_2O flux in alpine meadow.

Item	Model	r^2	*P* value
Month flux in 2004	y = 0.43x+0.11	0.35	<0.05
Month flux in 2005	y = 0.49x+0.15	0.37	<0.05
Annual flux	y = 1.05x	0.43	<0.01

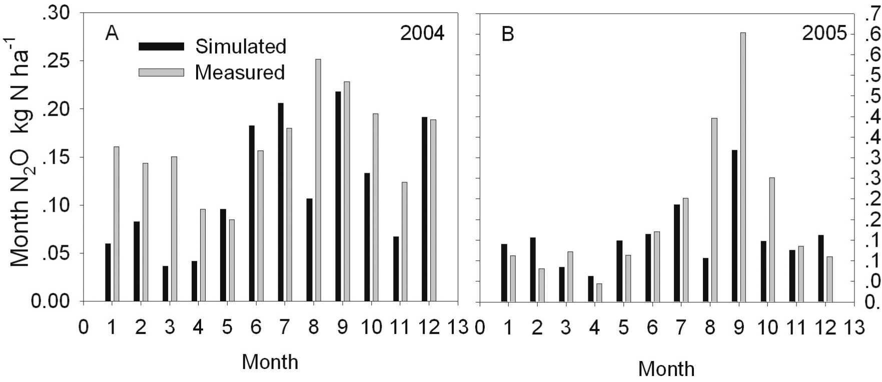

Fig. 2. Comparison of simulated and measured values of monthly cumulative N_2O flux.

DNDC slightly overestimated annual flux in 2004, but underestimated a little in 2005, and the relative deviations were below 20% (Table 3). The modeled results were significant correlated with observations ($P < 0.01$, $r^2 = 0.43$, Table 4).

4.3. Sensitivity analysis with DNDC model for dominant factors

In order to understand the sensitivity of modeled N_2O emissions to environmental factors, sensitivity tests were conducted by varying SOC content, pH, precipitation, ammonium and nitrate concentrations, and temperature by ±20% from the baseline input values (Table 5). In addition, soil temperature was changed by ±0.2°C (Fig. 3). Results from the tests indicated that N_2O flux was most sensitive to SOC variation. It increased steeply with the elevation of SOC content. Soil pH also significantly affected the flux, especially with other parameters the same as in 2005. Increase of soil pH led to decrease of N_2O emission in this alpine meadow. Variations in precipitation, ammonium and nitrate had relatively small effects on N_2O flux. N_2O emission was almost insensitive to variation of soil nitrate content up to ±20% (Table 5). It was highly sensitive to soil temperature change. When temperature raised by 0.2°C, the flux decreased by 16.5% and 2.2% in 2004 and 2005. However this increased 10.9% and 13.5% separately with temperature decreasing 0.2°C (Fig. 3).

5. DISCUSSION

5.1. Simulation of annual N_2O flux

Discrepancy should be expected between the IPCC Tier 2 method (i.e., empirical equations) and the Tier 3 method (using process-based models) for quantifying annual N_2O emissions at site scale (Nol *et al.* 2009). Since DNDC has included the most important external parameters driving N_2O production, the model could distinguish the inter-annual variations in N_2O emissions (Li *et al.* 1992b). Other researchers reported that DNDC estimated annual N_2O emissions with better results than that from the IPCC methodology (Saggar *et al.* 2004).

In this study, the annual N_2O flux of simulated and measured were 2.26 and 2.01

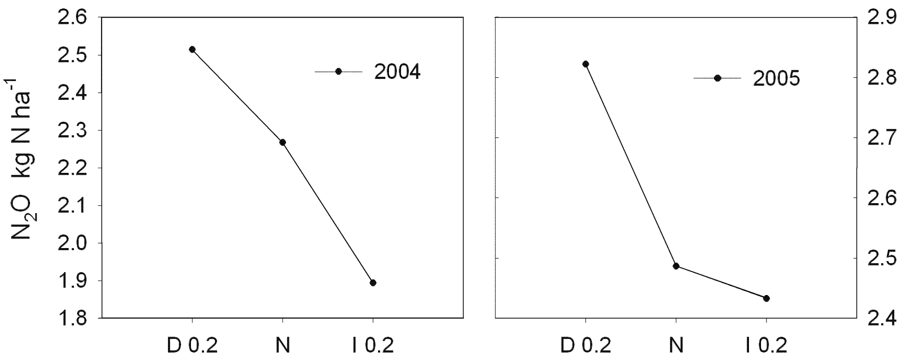

Fig. 3. Response of annual cumulative N_2O flux to air temperature. D 0.2, N and I 0.2 were the situation with air temperature decreased 0.2°C, normal and increased 0.2°C.

kg N_2O-N ha^{-1}, respectively for 2004, and 2.49 and 2.96 kg N ha^{-1}, respectively for 2005 (Table 3). The results are comparable with the N_2O emissions reported by other researchers. Xu *et al.* (2003b) reported that the DNDC-modeled and observed N_2O fluxes at a typical steppe in Inner Mongolian were 0.81 and 1.37 kg N ha^{-1}, respectively. In the temperate grasslands in western European average annual emission was 3 kg N_2O-N ha^{-1} with the maximum flux was 10 kg N_2O-N ha^{-1} for (Beheydt *et al.* 2007). Annual net emissions were 2.53 kg N_2O-N ha^{-1} in an unglazed cultivated grassland and about 10.41 kg N_2O-N ha^{-1} in the grazed areas in New Zealand (Saggar *et al.* 2004). Apparently, the geographic diversity of annual N_2O fluxes from grassland ecosystems was driven by the difference in climate (precipitation) and soil (organic matter content) conditions. High precipitation and SOC content favorite N_2O emissions from grasslands (Farquharson and Baldock 2008).

Comparison of our study with Xu's work, the typical steppe studied by Xu *et al.* (2003a) had much lower N_2O emissions with much higher deviation (40.08%) than the alpine meadow reported in this paper. It seemed that DNDC worked better for the ecosystems with higher N_2O emission rates, where usually have high SOC content and humid climate.

5.2. Sensitive factors for N_2O production

Modeling soil N_2O emission is a challenge because the relevant biological processes often respond differently to numerous influential factors, yet the effects of soil organic carbon content, moisture status, temperature, texture, and pH are far from being fully clarified and well incorporated in the models (Farquharson and Baldock 2008). In addition, some other factor, such as crop types and soil parameters, SOC partitioning could cause variations of simulated N_2O fluxes (Beheydt *et al.* 2007).

Soil organic carbon pools have been reported to be crucial in determining magnitude of spatial heterogeneity of N_2O fluxes (Cai *et al.* 2003, Xu *et al.* 2003b). Lower SOC content in the typical steppe in Inner Mongolia may partly lead to lower annual N_2O fluxes than the alpine meadow in this study (Xu *et al.* 2003b). SOC content also determined temporal variation of N_2O fluxes. A decrease of 15% in SOC content resulted in reduction of total N_2O fluxes by 0.2 to 14.6%, while an increase of 15% in SOC would elevate N_2O emission by 1.8 to 10.3% (Beheydt *et al.* 2007). In our study, the modeled annual N_2O emission increased by about 80% with a 20% increment of SOC content, and decreased by 50% with 20% reduction of SOC content (Table 5). SOC showed to be the key limiting factor in this study. This conclusion was consistent with other studies that indicated SOC content was the most sensitive factor for modeling N_2O fluxes with the DNDC model (Li *et al.* 1996, 2001). SOC influences N_2O emission in two ways: as energy source for heterotrophic denitrifiers and creation of anaerobic zones (Farquharson and Baldock 2008).

DNDC simulates change of soil pH due to flooding (Cai *et al.* 2003), and pH could have direct and indirect influences on rates and production of nitrification and denitrification (Farquharson and Baldock 2008).

Soil pH affects nitrogen transformation, such as nitrate reduction to ammonia (Stevens *et al.* 1998, Li *et al.* 2000). Simek *et al.*(2002) reported that 55% more of N_2O was released from an acidic soil than in a neutral soil, and about 58% less in alkaline soils in an alpine meadow. Extremely high or low pH could stimulate N_2O emissions (Simek *et al.* 2002), while Simek and Cooper (2002) reported that denitrification rates were less in acidic than in neutral or slightly alkaline soils.

Precipitation and soil moisture had been commonly accepted as important factors for N_2O production, thus change of precipitation was sought to explain modeled variation of N_2O flux in some studies (Cai *et al.* 2003). DNDC considered precipitation as a dominant driving force for N_2O flux from upland soil (Li *et al.* 1992a, Cai *et al.* 2003). High emission rate coincided with high soil moisture content in measurements (Saggar *et al.* 2004). N_2O emission from grassland soil was also reported to increase 12-fold as WFPS increased from 60 to 80% (Dobbie and Smith 2001). However, in this study, the modeled results showed that annual N_2O emission increased by only 2.02 and 0.38% when precipitation increased 20% from the baseline values in 2004 and 2005. It decreased by 6.63% when precipitation decreased 20% from that of 2005. It implied that total N_2O was insensitive to precipitation variation in this alpine meadow, probably due to high background value of rainfall at the site.

Despite of little effect on total N_2O flux in this case study, rainfall events promoted soil moisture content, and consequently decrease in soil aeration and enhance soil diffusion of nitrate. Thus it modified the relative contribution of nitrification and denitrification to total N_2O production. Soil water content (WFPS) was rarely high enough to promote denitrification in steppe in Inner Mongolia (Xu *et al.* 2003b). The lower rainfall led to a higher proportion of nitrification in total N_2O production (76%, Xu *et al.* 2003b) than the alpine meadow of this study (53%). Lower precipitation in 2005 was coincident with higher nitrification rate than that in 2004.

N supply including fertilization (Saggar *et al.* 2004, Beheydt *et al.* 2007), atmospheric N deposition and biological N fixation (Nol *et al.* 2009) stimulated total N_2O emissions to certain degree. Ammonium increased N_2O production through nitrification, while nitrate promoted denitrification process (Babu *et al.* 2006, Abdalla *et al.* 2009). The DNDC model gave out quite small response of total N_2O emission to either ammonium or nitrate variation in this alpine meadow, though positive correlation was demonstrated between soil N and annual N_2O flux (Table 5).

Higher temperature may promote activities of microorganisms and enzymes, so that an increase in the mean air temperature of 1.5°C resulting in almost 65% increase in the annual cumulative N_2O flux (Farquharson and Baldock 2008, Abdalla *et al.* 2009). However, warming reduced N_2O flux in this alpine meadow (Lin *et al.* 2009, Hu *et al.* 2010). Warming stimulated plant uptake of soil nitrate and soil water, leading to reduction of their contents in soil and denitrification rate. DNDC modeling gave out similar results as in situ measurement (Lin *et al.* 2009, Hu *et al.* 2010), with a reduction of annual N_2O emission by 16.5% and 2.5% when soil temperature increased 2°C from that of 2004 and 2005 (Table 5). This inferred that the alpine meadow would probably have a negative feedback on greenhouse gas.

Table 5. Response of N_2O flux to variation of input parameters from those of 2004 and 2005.

Factor	Year	Decreased 20% (%)	Increased 20% (%)
Soil organic carbon content	2004	−48.5	78.2
	2005	−50.3	79.2
Soil pH	2004	52.9	−38.2
	2005	58.4	−77.1
Precipitation	2004	−0.75	2.02
	2005	−6.63	0.38
Ammonium content	2004	−0.22	0.69
	2005	−9.04	0.78
Nitrate content	2004	−0.02	0.01
	2005	−0.05	0.05

5.3. Applicability of DNDC to alpine meadow

It had been pointed out by other researchers that there were discrepancies between simulated and measured N_2O emission for grassland or paddy soils (Cai *et al.* 2003, Beheydt *et al.* 2007). For example, the relative deviation on cumulative flux ranged from −237.8 to 28.6% for rice fields at different geographical locations in India (Babu *et al.* 2006). The relative deviation was about 36% in lowland soil because the modeled crop may be not accurate (Cai *et al.* 2003). The relative deviation was about 40% for a typical steppe in Inner Mongolia (Xu *et al.* 2003b). Relative deviations were 150 and 360% for mowing and grazed pasture, respectively, owing to overestimation of WFPS and the effect of soil organic carbon (Abdalla *et al.* 2009). DNDC model didn't capture N_2O fluxes from Irish grassland due to overestimation of SOC and WFPS (Abdalla *et al.* 2009).

In this study, the overall performance of DNDC was much better than that reported by other researchers, with deviations of less than 16% in the two years (Table 3). However, the model failed to capture the elevated emission rates in March and April (Figs. 1, 2), leading to underestimation in this period. DNDC tended to underestimate N_2O emissions during the soil freezing and thawing period as noticed in some former studies (Frolking *et al.* 1998, Stange *et al.* 2000, Xu *et al.* 2003b). Furthermore, the model failed to predict emissions from February to March most likely owing to overestimation of soil drying (Saggar *et al.* 2007).The fluxes of Autumn and September in 2005 were also underestimated in this alpine meadow. The performance of DNDC was fundamentally affected by its capacity of simulating dry and wet season transition, soil acidicity, and crop growth (Cai *et al.* 2003). The variability of controlling factors both in time and space resulted in highly heterogeneous emission. This was the main source of error in estimating and predicting soil N_2O emission (Mathieu *et al.* 2006).

Furthermore, grazing also affected N_2O and nitrogen budget because livestock removed biomass and litter from the fields, consequently decreased SOC content (Li *et al.* 2003). On the other hand, N_2O emissions may increase linearly with nitrogen supplied from livestock excreta and plant residues (Del Grosso 2010). Even process-based models were limited because it was difficult to properly represent wind velocity and topography affects snow movement and accumulation (Del Grosso 2010). The complicated nature of N_2O production and emission made it difficult to be accurately simulated, even by process-based models. Although discrepancies exist in the modeled results, the agreement between the measured and modeled annual N_2O fluxes suggested the applicability of DNDC for this alpine meadow. Further modifications may be needed to better represent the local circumstances such as crop rotation, soil type, transformation rate, climate, wind velocity, and topography that affected snow movement and accumulation (Xu *et al.* 2003a, Brown *et al.* 2004, Beheydt *et al.* 2007, Saggar *et al.* 2007).

The DNDC model has been proved powerful for estimating greenhouse gas emissions from terrestrial ecosystems with modifications based on local plant and soil conditions (Cai *et al.* 2003; Zhang *et al.* 2010). And it was effective to use DNDC for upscaling from site to regional scale (Babu *et al.* 2006). Besides, the model could help to identify strategies for optimizing resource use and reducing adverse environment impacts (Grant *et al.* 2004). Management practices played the greatest potential role to reduce both N_2O and CO_2 emissions (Babu *et al.* 2006). The sensitivity analysis of soil pH, temperature, SOC content, precipitation and soil N concentration were informative for management of the alpine meadow ecosystem.

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