PERGAMON

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Soil Biology & Biochemistry 35 (2003) 615–620

Soil Biology & Biochemistry

www.elsevier.com/locate/soilbio

Short communication

Using a modified DNDC model to estimate N_2O fluxes from semi-arid grassland in China

Xu-Ri*, M. Wang, Y. Wang

State Key Laboratory of Atmospheric Boundary Physics and Atmospheric Chemistry (LAPC), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China

Received 5 December 2001; received in revised form 23 December 2002; accepted 30 December 2002

Abstract

Field measurement results showed that approximately 40% of the annual N_2O losses occurred during the non-growing season and confirmed the importance of spring and autumn periods for assessment of total N_2O losses from semi-arid temperate grassland in China. In the previous study, we found that the 7.2 version of Denitrification–Decomposition (DNDC) model had significantly lower estimates of N_2O losses in spring and autumn time. In this study, three modifications, which mainly focus on the nitrification sub-model, the impact of soil frost and snow cover on gas production and emission, had been made to the model code. Based on field measurement, we concluded that modified version of DNDC model is more suitable for estimating the magnitude and seasonal trends of N_2O losses from this region on a plot scale. By extrapolating the field data with our modified model, we estimated that the annual N_2O emission rates for natural temperate grasslands of northern China is ca. $0.056T_g$ $N_2O{-}N$ y^{-1}, i.e. ca. 40% lower than the estimate based only on field measurements (ca. $0.092T_g$ $N_2O{-}N$ y^{-1}).
© 2003 Elsevier Science Ltd. All rights reserved.

Keywords: Nitrous oxide; Semi-arid grasslands; Revised DNDC modeling; Nitrification; Soil frost and snow cover

Nitrous oxide is one of the major greenhouse gases and also contributes to stratosphere ozone depletion. There is still considerable uncertainty in the global nitrous oxide budget (Bouwman et al., 2000). Because of the high variability of N_2O fluxes in both temporal and spatial scales, modeling approaches inevitably should be used to extrapolate field measurements from a limited number of sites to regional and global scales. Grasslands in China account for ca. 40% of the total country area and 78% of them are distributed in northern China (Chen and Wang, 2000), which contributes an important natural source for N_2O emission (Mosier et al., 1996). The natural grassland of the Xilin River basin, which is located in the centre of Inner Mongolian grassland, is a typical representation of semi-arid grassland of China. In a previous study there, we found that although the process based biogeochemical model Denitrification–Decomposition (DNDC) (Li, 2000; Li et al., 2000) captured the main process of N_2O emission during the entire growing season, it had significantly underestimated the magnitude of N_2O emission especially during the spring and autumn period, when the nitrification was the predominant process and the spring thaw event was involved (Xu-Ri et al., 2001). The aim of this study was to solve the above-mentioned problem in Version 7.2 of the DNDC (Li, 2000) and make it more suitable for simulating N_2O losses under the specific climatic conditions of the region.

Our study region is located in the Xilin River Basin of Inner Mongolia (43°26′–44°39′N, 115°32′–117°12′E), in northern China, where *Leymus chinensis* and *Stipa grandis* steppes are the two dominant vegetation types and represent ca. 60% of the total land area from East to the West (Li et al., 1988). Two permanent experimental sites (25 ha each) for *Leymus chinensis* steppe (LC, 43°32′N, 116°40′E) and *Stipa grandis* steppe (SG, 43°32′N, 116°33′E) were set up since 1980 with no grazing. Another sampling site is a free grazing area (GLC) outside of the *Leymus chinensis* steppe fence. They were classified as dark (LC and GLC) and typically (SG) Kastanozems (FAO, sandy loam) (Xiao et al., 1995). Details about the initial driving variables for the three sites for model runs including soil texture, surface soil N, C content and the above ground biomass were obtained from the relevant literature (Chen, 1988; Li, 1999; Wang

---

* Corresponding author. Tel.: +86-10-82013192.
E-mail address: xingxuri@yahoo.com (Xu-Ri), xr@dq.cern.ac.cn (X. Xuri).

0038-0717/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0038-0717(03)00009-9

Table 1
Initial driving variables of the three sites for model runs

	LC	GLC	SG
Bulk density (g cm^{-3})	1.18	1.40	1.21
Clay, % (<0.005 mm)	22.24	22.24	20.19
pH	7.2	7.6	8.2
Total *N* (%)	0.22	0.20	0.19
Organic *C* (%)	2.56	2.04	1.85
Wilting point (WFPS)	0.18	0.19	0.19
Field capacity (WFPS)	0.49	0.55	0.55
Optimum above ground biomass (Kg ha^{-1})	2500	1500	1600
Land use pattern	Fenced since 1980	Free grazing	Fenced since 1980

Abbreviation: LC = fenced *L. chinensis* site, GLC = free grazing *Leymus chinensis* site, SG = fenced *Stipa grandis* site.

and Cai, 1988; Li et al., 1988; Li and Chen, 1999; Gu and Li, 1997) (Table 1). Daily climate records were provided by Inner Mongolia Grassland Ecosystem Research Station, 43°37′49″N, 116°42′06″E.

The Xilin River Basin is within the continental temperate semi-arid grassland climate zone (Chen, 1988). Because of the low annual precipitation (ca. 350 mm yr^{-1}), rainfall infiltration in this area does not exceed 100 cm and only reaches 30–40 cm normally. Winter is cold and dry, while summer is warm and wet, and the soil water contents of the typical grasslands were always below field capacity (which is ca. 55% WFPS) over the whole year except during the heavy rainfall days in summer (Xu-Ri et al., 2001). The annual mean temperature is range from −1.5–2.5 °C (Chen, 1988).

By using a static closed chamber technique ($40 \times 40 \times 35$ cm) and gas chromatography equipped with Porapark Q and electronic capture detector, measurement of N_2O fluxes were conducted at the SG, LC, and GLC sites during 1998–1999. More detailed information about gas sampling and analyses were described by Xu-Ri et al. (2001). To further validate the revised DNDC model, we used the 1995 data set from SG and LC experimental sites published by Du et al. (1997).

Simulated and field measured N_2O flux rates were compared statistically using linear regression analysis with SPSS version 10.0 for windows. r^2 values from regression analyses were used to evaluate the model performance.

The modifications mainly focused on the following three aspects (Table 2)

(A) *Nitrification sub-model*. In the previous study, we found that nitrification was the dominant process and contributed approximately 76% of N_2O emission in typical grassland of Xilin River basin (Xuri et al., 2001). This result was consistent with the aerobic soil conditions in this region and also with a previous laboratory incubation experiment by using the acetylene-inhibition method (Du et al., 2000). Nitrification converts ammonium (NH_4^+) to nitrate (NO_3^-) via nitrite (NO_2^-) by a series of microbiological oxidation processes under aerobic conditions. N_2O can be produced as a byproduct or intermediate from this process (Li et al., 2000). Although NH_4^+ levels in grassland soil were mainly

Table 2
Modifications to the 7.2 version of DNDC model (Li, 2000; Li et al., 2000)

Model component	7.2 version of DNDC model	Modified DNDC in this study
(A) Nitrification induced N_2O (N_2O_N)	N_2O_N is only related to decomposition of soil organic carbon. $N_2O_N = 0.002R_n, R_n = R_{max}[NH_4]B_n pH$	If soil NH_4 exceeds background soil NH_4 levels (>3 mg-N kg^{-1}, levels found at most of the unfertilized grassland sites), N_2O gas fluxes from excess NH_4 are taken into account. $N_2O_N = 0.002R_n + N_{max}F_{NH_4}, F_{NH_4} = 1 - e^{-0.0105[NH_4\_e]}$ (Parton et al., 1996)
(B) Impact of low temperature on N_2O flux production	$N_2O[l]$ production is still active in both nitrification and denitrification sub models even at soil temperatures of certain layer below freezing (−1 °C).	In the nitrification and denitrification submodel, $N_2O[l]$ production of a frozen layer(below −1 °C) will be reduced to zero (in DNDC model 0–30 cm soil were divided into 15 layers) (Parton et al., 1998)
(C) Impact of soil frost on N_2O emission	If daily soil snow cover > 0 or freezing > 0 occurred at any layer in 0–30 cm. N_2O fluxes will be completely confined to the soil, $N_2O = 0$	If daily soil snow cover > 0 or freezing > 0 occurred at any layer in 0–30 cm. N_2O fluxes will not be completely confined, and assume 3% of the produced N_2O will emitted to the air (according to Röver et al. (1998)).

N_2O_N, N_2O production from nitrification; R_n = Nitrification rate; R_{max} = maximum nitrification rate; [NH_4], concentration of ammonium produced from soil organic carbon decomposition; B_n Biomass of nitrifiers; pH soil pH (Li et al., 2000); N_{max}, is the maximum nitrification N_2O gas flux with excess soil NH_4 (0.002 kg-N ha^{-1} d^{-1} $layer^{-1}$). F_{NH_4}, is the effect of excess soil NH_4 level on nitrification induced N_2O gas flux. [NH_4_e], excess soil NH_4 level in the aerobic condition (Parton et al., 1996); N_2O, daily N_2O fluxes (g-N d^{-1} ha^{-1}); $N_2O[l]$, N_2O gases production from a certain layer (1/h).

related to the decomposition of soil organic matter, excretion of N in animal dung and urine or metabolic substrate of N in plant litter also contributed to NH_4^+ levels. In the soil of typical grasslands of Xilin river basin, NH_4^+–N (3–14 mg-N kg^{-1}) concentration always exceeds background NH_4^+ levels (<3 mg-N kg^{-1}, levels found at most of the unfertilized grassland sites), almost 2–3 times greater than the NO_3^-–N concentration (1–6 mg-N kg^{-1}), and exhibited a high spatial variability (Li, 1999; Parton et al., 1996).

In the NGAS model, when the soil has a high level of NH_4^+, N_2O fluxes from excess NH_4^+ are calculated as a function of the soil NH_4^+ level (Parton et al., 1996). In the global Nitrogen Biosphere Model (NBM), the N_2O fluxes associated with excess N volatilized directly from soils were also estimated as a function of the soil inorganic N pool (Nevison et al., 1996). In the DNDC model, inorganic N availability to N_2O production was derived only from the decomposition process of soil organic matter and without considering the effect of high initial NH_4^+ levels. Table 2A, a simple equation was added to the nitrification sub-model of DNDC (Parton et al. 1996), to calculate the N_2O gas fluxes turnover from the excess soil NH_4^+ level.

(B) *Effect of low temperature on N_2O production*. As the result of microbial related nitrification and denitrification processes, production of N_2O was usually restricted by soil temperature and moisture especially in semi-arid temperate grassland. Measurement showed that N_2O fluxes were close to zero and with net uptake by the soil during dry autumn and frozen winter when the soil temperature(< -1 °C) and moisture (<20% WFPS) were both low (Xuri et al., 2001). There was a continuously higher N_2O emission (Fig. 1(b), around 1 g-N ha^{-1} d^{-1}) during the early spring when the top surface soil temperature was >0 °C and subsurface soil was still frozen (Fig. 1(a)) and soil moisture was ca. 30% WFPS (Li and Chen, 1999).

The top 0–30 cm of grassland soil is the most active site for N_2O production (Velthof and Oenema, 1995; Velthof et al., 1996; Ball et al. 1999). Velthof et al. (1996) suggested that when the surface soil was frozen, subsoil was a source

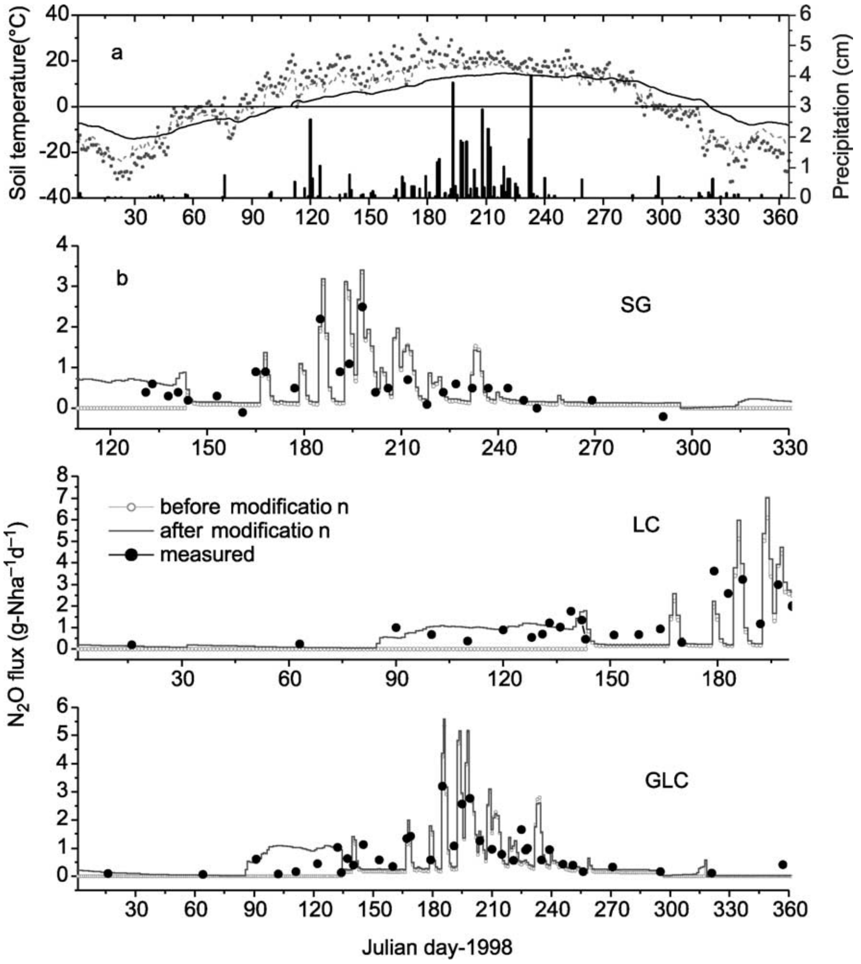

Fig. 1. (a) Daily precipitation (Bar), simulated (Dash line) and measured (Scatter) top surface soil temperature (0–5 cm), $r^2 = 0.96$, $p < 0.001$, and simulated subsurface soil temperature (Solid line) (15–30 cm) for the year 1998. (b) Comparison of the before and after modified DNDC simulations with field measured flux rates at different typical grassland site for the year 1998. Abbreviation: GLC = free grazing *Leymus chinensis* site, LC = fenced *L. chinensis* site, SG = fenced *Stipa grandis* site.

of N_2O in managed grasslands. In this study, we made the second modification to DNDC, based on the assumption that N_2O was only produced from the unfrozen layers of 0–30 cm soil profiles by nitrification. This means that if temperatures in the topsoil are below the frozen temperature, N_2O can be produced from the unfrozen subsurface soil. If subsurface soil was frozen, N_2O can be emitted from the thawing top surface soil. But if all of the soil profile is frozen (< -1 °C), there will be no N_2O flux (Fig. 1(a)).

Although Kaiser et al. (1998) and Röver et al. (1998) found higher N_2O fluxes (ca. 50 ug-N m^{-2} h^{-1}) even in frozen soils (soil temperature -4 °C) under arable management in Germany. Mosier et al. (1996) also measured high N_2O fluxes (>5 ug-N m^{-2} h^{-1}) during winter in Colorado short grass steppe, but the mechanisms of N_2O production were different in Inner Mongolian grasslands because of the different climatic conditions. Both studies found high flux rates during the winter when the water filled pore space was $>80\%$ and during periods of snowmelt. Denitrification was the main process (Röver et al., 1998; Mosier et al., 1996). However, in the semi-arid grasslands of Inner Mongolia, the winter is cold and dry (Fig. 1). There is only one possible snowmelt period, which is between late March to early April (90–120 Julian day), but the observed soil moisture (ca. 30% WFPS) during the spring thaw periods was rarely high enough to promote denitrification (Li and Chen, 1999). This explains the relative lower N_2O emission rates (<5 ug-N m^{-2} h^{-1} or 1 g-N ha^{-1} d^{-1}) during this period.

(C) *Impact of soil frost on the gas emission* (Table 2C). In the original DNDC model, N_2O fluxes to the atmosphere assumed to be zero when the soil was snow covered or frozen in any of the layers of 0–30 cm soil profiles (Li et al., 2000). This assumption is inconsistent with many published field measurements (Sommerfeld et al., 1993; Röver et al., 1998) that found N_2O emissions during the wintertime from snow-covered soils. Röver et al. (1998) reported a significant increase in N_2O concentrations below the snow cover, which indicates a restricted diffusion of N_2O through the snow. Field measurements conducted during the winter in the present snow covered grassland soils showed that N_2O flux rates were very low (<0.3 g-N ha^{-1} d^{-1}) (Xuri et al., 2001). In accordance with the field measurements, we assume that 3% of N_2O produced will diffuse to the air instead of being completely confined to the soil by snow cover or frozen soil layer.

Before modification (Table 3), the simulated N_2O fluxes in the LC site during spring and autumn accounted for only 1.4, and 37.3% of the field measurements. For the GLC and SG site, the percentages were 11.4, 42.0, and 2.76, 47.54%, respectively. In terms of magnitude, the accuracy of the model was poor, despite significant r^2 values ($r^2 = 0.56$, $r^2 = 0.68$, and $r^2 = 0.65$ for the LC, GLC, and SG site, respectively, $p < 0.001$). After revision, the accuracy of modeled estimates increased significantly (Fig. 1 and Table 3). By using the modified DNDC model, N_2O fluxes in LC, GLC and SG site during the spring and autumn period account for 93 and 85, 123 and 72, 108 and 109% of the field estimates, respectively.

In order to evaluate the performance of the above three modifications, we divided the three modifications into two groups (Table 3). The first group was B + C, the impact of low temperature on N_2O production and impact of soil frost

Table 3

Comparison of the different modified modeling results with field measurements at LC, GLC, and SG site, Inner Mongolian during 1998. The first group was B + C, the impact of low temperature on N_2O production and impact of soil frost on N_2O emission. The second group was A + B + C, to further take account of high soil initial NH_4^+ levels

Site	Season	Simulated N_2O g-N ha^{-1} d^{-1}			Measured N_2O g-N ha^{-1} d^{-1}
		Before modification of DNDC	After modification of DNDC B + C	After modification of DNDC A + B + C	
LC	Spring	0.012	0.772	0.789	0.848
	Summer	1.300	1.288	1.435	1.421
	Autumn	0.091	0.160	0.207	0.243
	Winter	0.0	0.134	0.134	0.196[a]
	r^2	0.56	0.42	0.50	–
GLC	Spring	0.053	0.526	0.571	0.465
	Summer	1.100	1.100	1.175	1.251
	Autumn	0.111	0.129	0.191	0.265
	Winter	0.0	0.076	0.072	0.249[a]
	r^2	0.68	0.54	0.60	–
SG	Spring	0.011	0.401	0.425	0.394
	Summer	0.650	0.650	0.712	0.763
	Autumn	0.061	0.103	0.140	0.128
	Winter	0.0	0.081	0.081	–
	r^2	0.65	0.66	0.66	–

The duration of spring is Julian day 60–150, summer is 151–243, and autumn is 244–334.

[a] Winter time measurement was very sparse, the values listed in this table were the average of two observation.

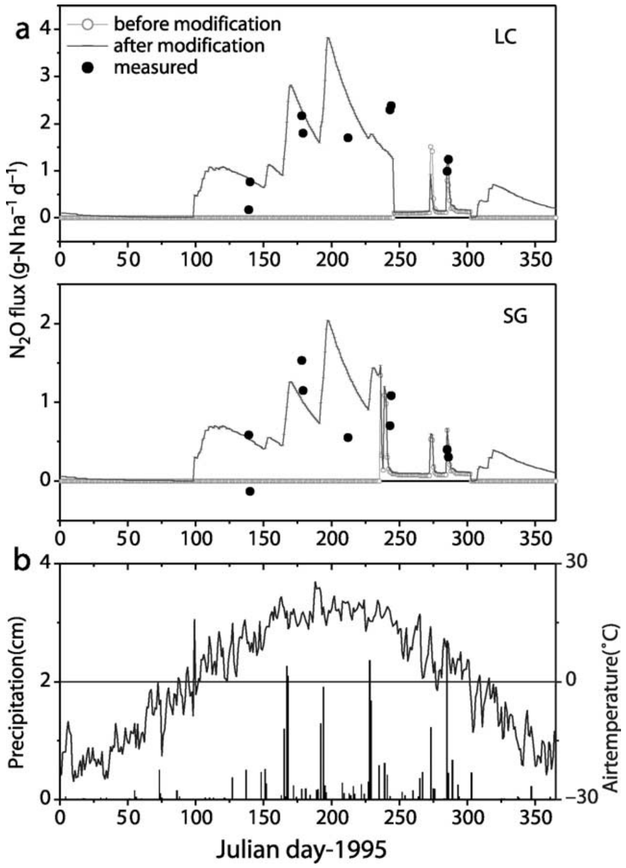

Fig. 2. (a) Comparison of the before and after modified DNDC simulations with field measured flux rates at different typical grassland site for the year 1995. Abbreviation: LC = fenced *L. chinensis* site, SG = fenced *Stipa grandis* site. Field date from Du et al. (1997). (b) Daily precipitation (Bar) and air temperature (Solid line) for the year 1995.

on N_2O emission. The second group was A + B + C, to take account of high soil initial NH_4^+ levels. Table 3 shows that with the B + C modification, modeling accuracy was increased notably especially during spring and autumn and also in winter, and had significant r^2 values ($r^2 = 0.42$, 0.54, and 0.66 in LC, GLC, and SG site, respectively, $p < 0.001$). The values during the winter listed in Table 3 were the average of only two measurements. Because negative fluxes were frequently measured on the other sites in this region during winter (Xu-Ri et al., 2001), the actual average winter N_2O flux rates should be lower than the average of measured two values. The results also indicated that the modification A + B + C further improved the r^2 values ($r^2 = 0.50$, 0.60, and 0.66 for the LC, GLC and SG site, respectively) and the modeling accuracy in terms of magnitude, particularly for the summer (Table 3). However, compared with the modification B + C, adding modification A was not a crucial step in improving DNDC 7.2, but was necessary for improving overall modeling accuracy and for further evaluating the effect of spatial variability of NH_4^+ level on N_2O emission.

To further validate our modification, we used the revised model to simulate the N_2O fluxes observed in same location sites LC and SG during 1995 (Du et al., 1997) and without changing any of the internal parameters that were used previously modeling (Fig. 2). During 1995, the observation times were limited to the growing season and it was impossible for us to do any statistical analysis because there were only two observations per month. However, after our modification, the timing and relative magnitude of N_2O fluxes from simulation are consistent with the field observations, and the modeled outputs more closely followed the field measurements than before (Fig. 2).

One of the major roles of modeling is to enable extrapolation of the measurement to larger temporal and spatial scales. According to the above analysis of case studies, using the process-based model to track N_2O emission is an important mechanism but require modification to fit the actual conditions of the area. In Table 4, we found that before modification, the accuracy of DNDC was poor, especially during 1995. If the annual emission rate of N_2O estimation were based only on the limited field measurement data from this region, we would over-estimate the actual annual flux rate by ca. 40%. According to our revised model, the average annual N_2O emission rate is ca. 18.1 mg-N m^{-2} y^{-1}. If we assume our grassland sites to be typical, N_2O emission from grasslands of northern China (ca. 3.13×10^{12} m^2, Chen and Wang, 2000) averaged $0.056 T_g$ yr^{-1}.

Table 4
Comparison of the estimate of annual average N_2O emission rates with DNDC modeling approach and field measurements

Year	Sites	Annual average N_2O flux rates mg-N m^{-2} yr^{-1}		
		Before DNDC modification	After DNDC modification	Field measurements (number of observations)
1998	LC	12.9	23.5	38.4 (38)
	GLC	11.7	18.5	29.6 (36)
	SG	6.7	12.5	21.1 (27)
1995	LC	1.1	28.0	61.2 (9)[a]
	SG	1.2	15.3	26.8 (9)[a]

[a] Field measurements cited from Du et al. (1997).

Acknowledgements

This research was funded by the grant of the Knowledge Innovation Program (CBTSEC) of Chinese Academy of Sciences (approved # KZCX1-SW-01). We sincerely thank Prof. Changsheng Li for providing the code of the DNDC model and made a detailed revision on this manuscript. Thanks are also given to the two anonymous reviewers and Dr Haishan Niu who read the manuscript and made a number of helpful comments.

References

Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil and Tillage Research 53, 29–39.

Bouwman, A.F., Taylar, J.A., Kroeze, C., 2000. Testing hypotheses on global emissions of nitrous oxide using atmospheric models. Chemosphere—Global Change Science 2, 475–492.

Chen, Z.Z., 1988. Topography and climate of the Xilin River basin. Inner Mongolia Grassland Ecosystem Research Station (Ed.), Research on Grassland Ecosystem, No. 3. China Scientific Press, Beijing. pp. 13–22, in Chinese with English abstract.

Chen, Z.Z., Wang, S.P., 2000. Typical Grassland Ecosystem of China, China Scientific Press, Beijing, pp. 228–244, in Chinese.

Du, R., Chen, G.X., Lu, D.R., Wang, G.C., 1997. Primary research in situ measurements of N_2O and CH_4 fluxes from Inner Mongolia grassland ecosystem. Climatic and Environmental Research 2, 265–272.in Chinese, with English abstract.

Du, R., Wang, G.C., Lu, D.R., 2000. The mechanism of N_2O production in typical grassland soils of Inner Mongolia. China Environmental Science 20, 387–391.In Chinese, with English abstract.

Gu, X.Y., Li, S.Q., 1997. Influence of grazing intensity on the submicroscopic features in steppe soils. Inner Mongolia Grassland Ecosystem Research Station (Ed.), Research on Grassland Ecosystem, No. 3. China Scientific Press, Beijing. pp. 80–87, in Chinese with English abstract.

Kaiser, E.-A., Kohrs, K., Kücke, M., Schnug, E., Heinemeyer, O., Munch, J.C., 1998. Nitrous oxide release from arable soil: importance of N-fertilization, crops and temporal variation. Soil Biology and Biochemistry 30, 1553–1563.

Li, X.Z., 1999. Effects of grazing on characteristics of carbon, nitrogen, phosphorus pools in soil-plant system of typical steppe. PhD Thesis, Institute of Botany, Chinese Academy of Science, Beijing.

Li, C.S., 2000. Modeling trace gas emission from agricultural ecosystems. Nutrient Cycling in Agroecosystems 58, 259–276.

Li, S.L., Chen, Y.J., 1999. Study on the soil water dynamic and physical characteristic of chestnut soil in Xilin River. Grassland of China 3, 71–76.

Li, B., Yong, S.P., Li, Z.H., 1988. Vegetation of the Xilin river basin and its utilization. Inner Mongolia Grassland Ecosystem Research Station (Ed.), Research on Grassland Ecosystem, No. 3. China Scientific Press, Beijing. pp. 84–183, in Chinese with English abstract.

Li, C., Aber, J., Stange, F., Butterbach-Bahl, K., Papen, H., 2000. A process-oriented model of N_2O and NO emission from forest soils: 1, model development. Journal of Geophysics Research 105, 4369–4384.

Mosier, A.R., Parton, W.J., Valentine, D.W., Ojima, D.S., Schimel, D.S., Delgado, J.A., 1996. CH_4 and N_2O fluxes in the Colorado shortgrass steppe, 1, impact of landscape and nitrogen addition. Global Biogeochemistry Cycles 10, 387–399.

Nevison, C.D., Esser, G., Holland, E.A., 1996. A global model of changing N_2O emissions from natural and perturbed soils. Climate Change 32, 327–378.

Parton, W.J., Hartman, M., Ojima, D., Schimel, D., 1998. DAYCENT and its land surface submodel: description and testing. Global and Planetary Change 19, 35–48.

Parton, W.J., Mosier, A.R., Ojima, D.S., Valentine, D.W., Schimel, D.S., Weier, K., Kulmala, A.E., 1996. Generalized model for N_2 and N_2O production from nitrification and denitrification. Global Biogeochemistry Cycles 10, 401–412.

Röver, M., Heinemeyer, O., Kaiser, E.-A., 1998. Microbial induced nitrous oxide emissions from an arable soil during winter. Soil Biology and Biochemistry 30, 1859–1865.

Sommerfeld, R.A., Mosier, A.R., Messelman, R.C., 1993. CO_2, CH_4 and N_2O flux through a Wyoming snow pack and implications for global budgets. Nature 361, 140–142.

Velthof, G.L., Oenema, O., 1995. Nitrous oxide fluxes from grassland in Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing. European Journal of Soil Science 46, 540–541.

Velthof, G.L., Brader, A.B., Oenema, O., 1996. Seasonal variations in nitrous oxide losses from managed grasslands in the Netherlands. Plant and Soil 181, 263–274.

Wang, J.W., Cai, W.C., 1988. Studies on genesis, types and characteristics of soils of Xilin river basin. Inner Mongolia Grassland Ecosystem Research Station (Ed.), Research on Grassland Ecosystem, No. 3. China Scientific Press, Beijing. pp. 23–83, in Chinese with English abstract.

Xiao, X.M., Wang, Y.F., Jiang, S., Ojima, D.S., Bonham, C.D., 1995. Interannual variation in the climate and above-ground biomass of *leymus chinense* steppe and *Stipa grandis* steppe in the Xilin river basin, Inner Mongolia, China. Journal of Arid Environments 31, 283–299.

Xu-Ri, Wang, Y.S., Zheng, X.H., Ji, B.M., Wang, M.X., 2001. A comparison between measured and modeled N_2O emissions from Inner Mongolian semi-arid grassland. In the third review by the Plant and Soil.