Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 20(2008) 339–346
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Modeling effects of temperature and precipitation on carbon characteristics and GHGs emissions in *Abies fabric* forest of subalpine

LU Xuyang[1,2], CHENG Genwei[1,*], XIAO Feipeng[1,2], FAN Jihui[1]

1. Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China
2. Graduate School of the Chinese Academy of Sciences, Beijing 100039, China E-mail: luxuyang@126.com

Received 31 May 2007; revised 25 July 2007; accepted 14 August 2007

Abstract

Abies fabric forest in the eastern slope of Gongga mountain is one type of subalpine dark coniferous forests of southwestern China. It is located on the southeastern edge of the Qinghai-Tibet plateau and is sensitive to climatic changes. A process-oriented biogeochemical model, Forest-DNDC, was applied to simulate the effects of climatic factors, temperature and precipitation changes on carbon characteristics, and greenhouse gases (GHGs) emissions in *A. fabric* forest. Validation indicated that the Forest-DNDC could be used to predict carbon characteristics and GHGs emissions with reasonable accuracy. The model simulated carbon fluxes, soil carbon dynamics, soil CO_2, N_2O, and NO emissions with the changes of temperature and precipitation conditions. The results showed that with variation in the baseline temperature from –2°C to +2°C, the gross primary production (GPP) and soil organic carbon (SOC) increased, and the net primary production (NPP) and net ecosystem production (NEP) decreased because of higher respiration rate. With increasing baseline precipitation the GPP and NPP increased slightly, and the NEP and SOC showed decreasing trend. Soil CO_2 emissions increased with the increase of temperature, and CO_2 emissions changed little with increased baseline precipitation. With increased temperature and decreased baseline temperature, the total annual soil N_2O emissions increased. With the variation of baseline temperature from –2°C to +2°C, the total annual soil NO emissions increased. The total annual N_2O and NO emissions showed increasing trends with the increase of precipitation. The biogeochemical simulation of the typical forest indicated that temperature changes strongly affected carbon fluxes, soil carbon dynamics, and soil GHGs emissions. The precipitation was not a principal factor affecting carbon fluxes, soil carbon dynamics, and soil CO_2 emissions, but changes in precipitation could exert strong effect on soil N_2O and NO emissions.

Key words: carbon characteristics; greenhouse gases (GHGs); Forest-DNDC; *Abies fabric* forest

Introduction

Increasing emissions of carbon dioxide (CO_2), nitric oxide (NO), nitrous oxide (N_2O), and other greenhouse gases (GHGs) are believed to contribute to global warming. A recent Intergovernmental Panel on Climate Change (IPCC) has reported the global warming and forecasted a rise in mean global surface temperature of 1.4–5.8°C by the year 2100 (IPCC, 2001). The sphere of global influence and the complexity of the study processes have also made it become the current core subject of many international research programs (IGBP-WCRP-IHDP) and the major topics of numerous international negotiations environmental issues (Dong *et al*., 2003). Forests are the most extensively distributed vegetation-type ecosystems in the world and cover approximately one-third of the earth land surface (Li *et al*., 2000). Forests are an important component of the terrestrial landscapes that exert a considerable influence over global carbon cycle, source and sink function of GHGs.

Carbon characteristics, GHGs emissions in forests are a function of complex interactions of inherent soil process, climate, vegetation, time, and disturbance. Carbon characteristics and CO_2 emission are mostly controlled by photosynthesis, respiration, and decomposition (Cui *et al*., 2005b; Zhang *et al*., 2002). Biotic processes (mainly nitrification and denitrification) as well as abiotic processes (e.g. diffusion and chemodenitrification) are involved in production, consumption, and emission of NO and N_2O from soil. All these process interact with a number of environment factors including temperature, moisture, pH, Eh, and substrate availability (Butterbach-Bahl *et al*., 2000). As temperature and precipitation govern most biological processes in forest ecosystems, they are also connected to carbon dynamics and GHGs emissions. To link temperature and precipitation with carbon dynamics and GHGs emissions, a comprehensive model is needed to simulate how carbon characteristics and GHGs emissions respond to the changes of temperature and precipitation conditions.

Forest-DNDC is a process-oriented model based on the biogeochemical cycling of C and N in forest and wetland ecosystems, which was developed by some researchers.

* Corresponding author. E-mail: gwcheng@imde.ac.cn.

(Li *et al*., 2000; Butterbach-Bahl *et al*., 2000; Zhang *et al*., 2002; Cui *et al*., 2005a). This model can predict forest growth and production, soil carbon and nitrogen dynamics, and carbon sequestration and soil-borne trace gas emissions in upland and wetland forest ecosystems. Minimum input parameters required by the model are daily air temperature, precipitation, ambient CO_2 concentration, N concentration in precipitation, humus layer type , litter layer type, bypass flow, mineral soil texture, mineral soil pH, stone content, organic carbon content, depth to groundwater level, latitude, management operations, and so on (Miehle *et al*., 2006b). The model can run from a year to several decades with a primary time of one day. This temporal scale allows us to directly use field observations to validate the model, and to answer questions about climatic changes and management practices. In this article, we investigate Forest-DNDC to predict the effect of changes of temperature and precipitation conditions on carbon characteristics and GHGs emissions in an *Abies fabric* forest ecosystem.

1 Materials and methods

1.1 Model description

The Forest-DNDC model integrates two existing models: PnET-N-DNDC, an upland forest biogeochemical model, and Wetlands-DNDC, a hydrology-driven model (Miehle *et al*., 2006a). The PnET-N-DNDC was initially developed to predict soil carbon and nitrogen biogeochemistry in forest ecosystems. In the PnET-N-DNDC model, carbon and nitrogen biogeochemical characteristics are directly influenced by environmental factors, such as soil temperature and moisture, pH, and substrate availability (C and N content). These environmental factors are driven by different ecological drivers, namely climate, soil properties, vegetation, and anthropogenic activities. The PnET-N-DNDC model (from photosynthesis and evapotranspiration-nitrification-denitrification and decomposition) consists of two components. The first component includes three submodels for soil climate, forest growth, and decomposition. On the basis of daily climate data (temperature and precipitation), soil physical properties, and by considering plant and microbial turnover processes of C, N, and water, the soil climate submodel calculates temperature, moisture, and oxygen profiles derived from one-dimensional thermal-hydraulic flow, and gas diffusion equations. The forest growth submodel simulates forest growth as a function of solar radiation, temperature, water, and N availability. The forest growth module is linked to the soil climate and the decomposition modules via litter production, water, and N demand. The decomposition submodel quantifies the decomposition of organic matter resulting in substrate concentrations of dissolved organic carbon (DOC), NH_4^+, and CO_2, based on decay rates depending on organic matter quality and soil environmental conditions (temperature, moisture, and O_2 availability). The second component includes two submodels for nitrification and denitrification. In nitrification or denitrification submodels, ammonium, nitrate, and DOC come from the decomposition submodel tracks turnover of the litter and other organic matter in the soil. The nitrification submodel predicts growth and death of nitrifiers, with the nitrification rate as well as NO and N_2O productions from nitrification depending on soil temperature, moisture, ammonium, and DOC concentration. The denitrification submodel simulates the individual steps of the sequential reduction of nitrate or other oxidized N compounds (NO_2^-, NO, N_2O) to the final product N_2 based on the population size of denitrifiers, soil temperature, moisture, and substrate concentrations (DOC, NO_3^-, NO_2^-, NO, and N_2O) (Li *et al.*, 2000; Butterbach-Bahl *et al*., 2000, 2001; Kiese *et al*., 2005; Kesik *et al*., 2005, 2006; Miehle *et al*., 2006a, 2006b).

The nitrification and denitrification induced N_2O, NO, and N_2 fluxes are calculated based on simulated soil microbial activities, which depend on simulated soil environmental conditions, and a series of biochemical and geochemical reactions determining the transport and transformation of C and N components. Chemodenitrification, i.e. chemical decomposition of NO_2^- to NO, is considered as another source of NO production in soils. This chemical reaction is controlled by the concentration of nitrite in the soil, soil pH, and temperature, which occurs only when soil pH is < 5.0 (Li *et al*., 2000). It was assumed that the main source of nitrite in soils is nitrification because rates of nitrification in forest soils (200–1000 kgN/(hm^2·a)) are usually higher than rates of denitrification (< 50 kgN/(hm^2·a)) (Butterbach-Bahl *et al*., 2000, 2001). To handle the problem of simultaneously occurring aerobic and anaerobic processes in adjacent microsites, the PnET-N-DNDC model uses the concept of a so-called "anaerobic balloon". The O_2 concentration is calculated for a given soil layer based on the O_2 diffusion from the atmosphere into the soil and the O_2 consumption during heterotrophic and autotrophic respiration. The O_2 concentration is assumed to be reciprocally proportional to the anaerobic fraction within this soil layer (Li *et al*., 2000; Kesik *et al*., 2005).

Wetland-DNDC, which was developed for predicting C and N biogeochemistry and in forested wetland ecosystems was constructed by incorporating hydrological features into the PnET-N-DNDC model. The basic functions adopted by Wetland-DNDC model are to simulate forest growth, soil biogeochemistry, and hydrological processes. To make the model capable of predicting effects of management on water, C and N biogeochemical cycles, and make the model prepare for use in a spatial simulation Wetland-DNDC model has been modified by some researchers (Li *et al*., 2004; Cui *et al*., 2005a, 2005b, 2005c). The Forest-DNDC model have been successfully tested and applied in many countries and land use scenarios. Further details on model development (Li *et al*., 1992a, 2000, Zhang *et al*., 2002; Cui *et al*., 2005a), validation (Smith *et al.*, 1997, 2002; Stange *et al*., 2000; Kiese *et al*., 2005; Kesik *et al*., 2005; Miehle *et al*., 2006a, 2006b), regional applications, and multiscale testing (Li *et al*., 1992b, 2005; Brown *et al*., 2002; Butterbach-Bahl *et al.*, 2001, 2004), are available from the cited publications.

1.2 Study site description and simulation scenarios

The *A. fabric* forest is mountainous, dark, coniferous forest located in 3000 m altitude in the Gongga mountain. Gongga mountain is located to the southeast of the Tibetan plateau between 29°20′–30°20′N and 101°30′–102°15′E. It belongs to the category of subtropical monsoon climate. A complete, natural vertical spectrum ranging from subtropical to alpine cold vegetation was very well developed in the area. The *A. fabric* forest in this study is middle age forest, which sites in 3000 m altitude and eastern slope of Gongga mountain. This forest rooted in the blank of primeval *A. fabri* forest was destroyed by the debris flows and has developed into the mid-aged forest with a tree age of about 80-years following plant succession. The constructive species is *A. fabri*. The *A. fabri* is about 18-m high and the breast-height diameter is 20–30 cm. Under arbor layer, there are some sparse scrubs and herbage with cover degree being smaller than 30% each. The annual mean air temperature of this area is 3.8°C, mean air temperature of January is −4.3°C and that of July is 11.9°C. The average precipitation is 2,175.4 mm, mostly concentrating in June–September and accounting for 60.6% of the year's total. The detailed features and information about this site can be found in some literatures (Zhang *et al.*, 2003; Dong *et al.*, 2003; Cheng and Luo, 2003, 2004; Wang *et al.*, 2004, 2005).

Daily maximum and minimum air temperature and precipitation were derived from the continuous data records for the site and used to generate model results. Daily average maximum and minimum air temperature, daily average sum of precipitation, which calculated from a 6-year dataset each today's climate from 1999 to 2004 were assumed as the baseline scenario (Fig.1). To predict the effect of changes of temperature and precipitation conditions on carbon characteristics and GHGs emissions, the baseline temperature varied from ±1°C to ±2°C, and the baseline precipitation varied from ±10% to ±20% were designed. And model was run by varying one model driver (air temperature, precipitation) and keeping other drivers and model input parameters constant.

1.3 Model validation

Model validation is to test the degree of agreement between simulated values and measured values. The Forest-DNDC has been validated by all kinds of forest types in many countries, such as the United States (pine and oak), Denmark (spruce), Austria (beech), Germany (spruce and beech), and Australia (Eucalyptus and rainforest) (Stange *et al.*, 2000; Kiese *et al.*, 2005; Kesik *et al.*, 2005; Cui *et al.*, 2005b; Miehle *et al.*, 2006a, 2006b). The result showed that simulated and measured values were in general agreement in terms of magnitude and seasonal pattern. The six months daily soil CO_2 emissions data from May 1 to October 31 in 1998 were measured for

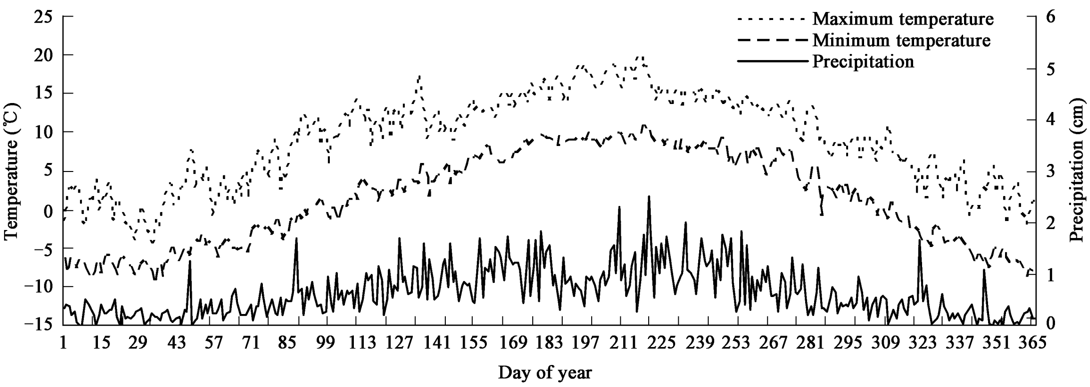

Fig. 1 Daily average maximum and minimum air temperature, daily average sum of precipitation, which calculated from a 6-year dataset climate from 1999 to 2004 in *Abies fabric* forest.

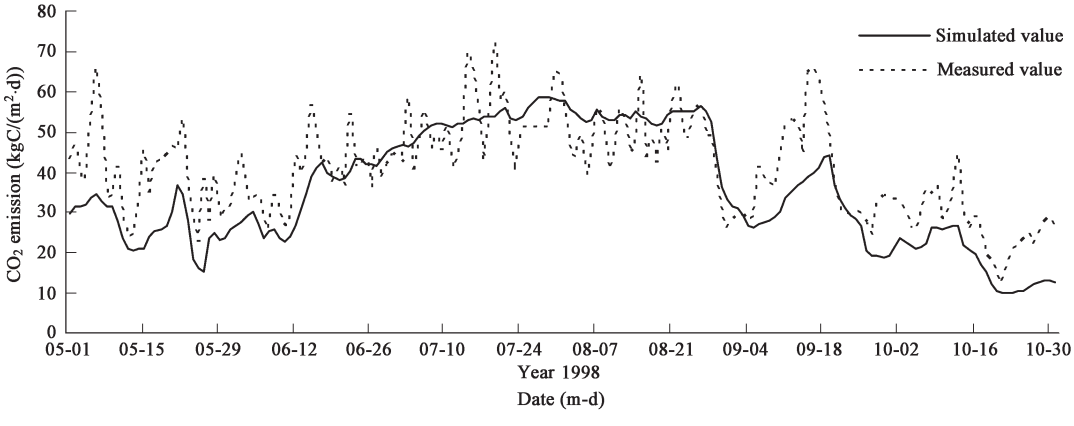

Fig. 2 Comparisons between simulated and measured daily soil CO_2 emissions from 1 May to 31 October in 1998 in *Abies fabric* forest.

model validation (Fig.2). The model soil CO_2 emissions corresponded well to the trends and temporal variations of measured values. Comparison between simulated and measured quantities of soil CO_2 emission showed good agreement (R^2 = 0.613). Few soil NO and N_2O emission data in *A. fabric* forest were observed for model validation. Dong *et al.* (2003) measured average daily soil N_2O emission from middle age *A. fabri* forest as 0.43–5.58 gN/(hm^2·d). The Forest-DNDC estimated average daily soil N_2O emission was 1.40 gN/(hm^2·d) and was in the range of measured value. The results obtained from validation studies indicated that the Forest-DNDC can be used to predict carbon characteristics and GHGs emissions in *A. fabric* forest with reasonable accuracy.

2 Results and discussion

2.1 Effect of temperature and precipitation on carbon characteristics

2.1.1 Carbon fluxes

In forest ecosystems, carbon is contained in the standing vegetations and in litter and organic soils. The processes of photosynthesis and respiration are functions of several environmental and plant variables, including solar radiation, air, temperature and humidity, availability of water and nutrients, leaf area, and foliar nutrition. The results predicted carbon fluxes with variation in the baseline temperature from ±1°C to ±2°C (Fig.3a). The simulated gross primary production (GPP) of *A. fabric* forest was strongly affected by temperature. The GPP increased with increasing temperature, and it meant that trees and other vegetation grew quickly at high temperatures. With variation in the baseline temperature from –2°C to +2°C, GPP increased from 17,847 to 28,350 kgC/(hm^2·a). Net primary production (NPP) is GPP minus the flux of autotrophic respiration of assimilate used for plant's own metabolism. Net ecosystem production (NEP) is a measure of the production of total ecosystem and is equivalent to NPP minus soil microbial respiration. Both NPP and NEP showed decreasing trends with variation in the baseline temperature from –2°C to +2°C. Despite significantly elevated GPP with the increasing temperature, the total NPP and NEP did not show increasing trend like as GPP, because forest with higher temperature also generated more litter and consequently have higher respiration rates, which includes autotrophic respiration and heterotrophic respiration. With variation in the baseline temperature +2°C, the total NPP and NEP were the lowest, decreased 28.3% and 70.6%, respectively, compared with the baseline temperature. Fig.3b shows the simulation carbon fluxes with variation in the baseline precipitation from ±10% to ±20%. The carbon fluxes changed slightly with increasing precipitation. With variation in the baseline precipitation from ±10% to ±20%, the GPP and NPP showed increasing trends. But with 120% precipitation, it only increased 0.01% and 4.17% compared with 80% precipitation. The total NEP showed decreasing trend because soil microbial respiration improved at higher precipitation rates.

2.1.2 Soil carbon dynamics

Soil carbon is determined by the balance between litter input and soil heterotrophic respiration in forest ecosystems. It was clear that soil carbon was influenced by the changes of temperature condition (Figs.4a and 4b). With temperature increasing, the annual changes of SOC decreased on both forest floor and mineral soil. With variation in the baseline temperature +2°C, the annual changes of SOC were the lowest, 4,009 kgC/(hm^2·a) on forest floor and 2,260 kgC/(hm^2·a) on the mineral soil, respectively. With the changes in temperature, the annual changes of humads and humus on forest floor changes little, average −113 and 12.2 kgC/(hm^2·a), respectively. The annual changes of humads and humus in the mineral soil showed increasing trends, improved 39.9% and 30%, respectively, with a variation in the baseline temperature +2°C compared with the baseline temperature. So, the rate of a number of processes was affected by temperature that in turn affected the soil carbon dynamics. The higher temperature caused a decrease of the changes of SOC because of greater proportion of carbon was respired during decomposition of soil carbon pools. Figs.4c and 4d show the annual soil carbon changes in *A. fabric* forest with alteration in precipitation. The annual changes of

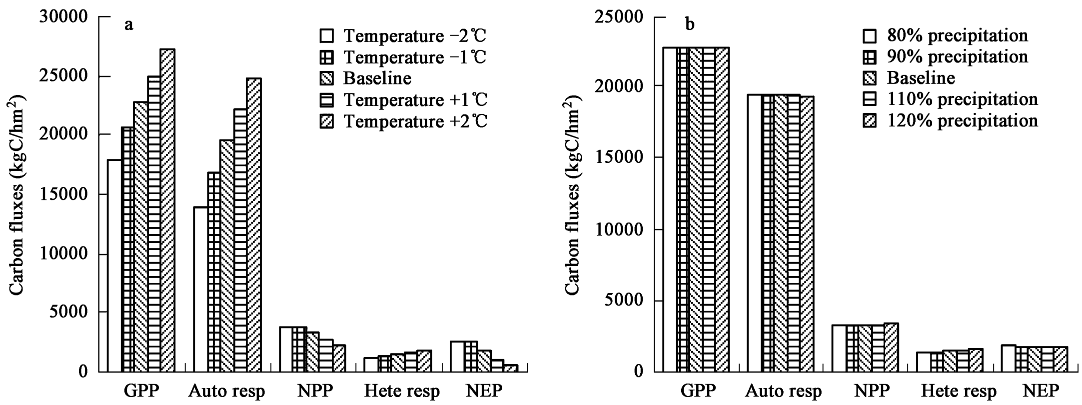

Fig. 3 Simulated carbon fluxes of *Abies fabric* forest for the two simulation scenarios. (a) variation in the temperature from ±1°C to ±2°C; (b) variation in the precipitation from ±10% to ±20%. GPP: gross primary production; Auto rasp: autotropic respiration; NPP: net primary production; Hete resp: heterotropic respiration; NEP: net ecosystem production.

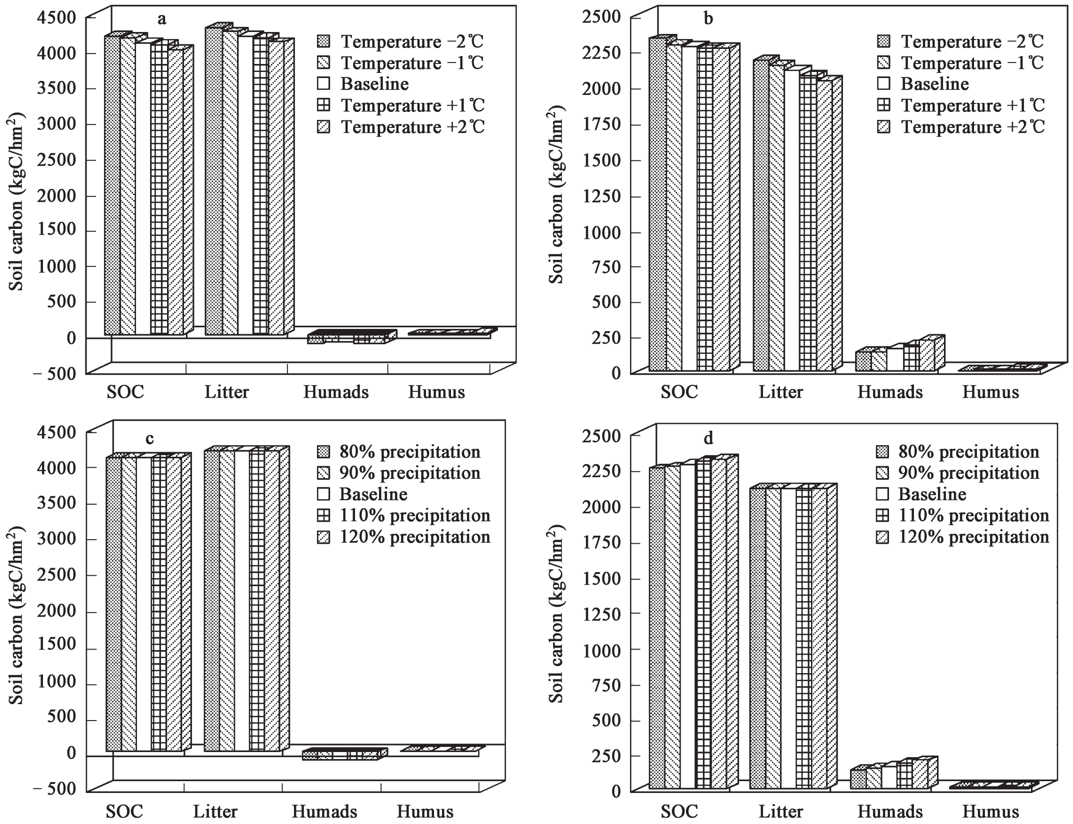

Fig. 4 Simulated annual soil carbon changes in *A. fabric* forest for the two simulation scenarios. (a) changes of soil carbon on forest floor with variation in the temperature from ±1°C to ±2°C; (b) changes of soil carbon on mineral soil with variation in the temperature from ±1°C to ±2°C; (c) changes of soil carbon on forest floor with variation in the precipitation from ±10% to ±20%; (d) changes of soil carbon on mineral soil with variation in the precipitation from ±10% to ±20%.

SOC increased on both forest floor and the mineral soil with variation in the baseline precipitation from ±10% to ±20%. The annual changes of humads also increased with increasing precipitation but the humus kept steadiness. Increasing precipitation leads to an increase in soil carbon stock was because the rate of decomposition of soil carbon was decreased.

2.2 Effect of temperature and precipitation on GHGs emissions

2.2.1 CO_2 emission

In this study, CO_2 emission is defined as the summation of microbial respiration and root respiration. CO_2 are the end products of organic matter decomposition in forest soils. The CO_2 emission rates from forest soil reflect variations in temperature, moisture, and other environmental factors. Fig.5 shows the simulated total CO_2 emissions from the soil of *A. fabric* forest with variation in the baseline temperature from ±1°C to ±2°C. The seasonal variation of CO_2 emissions followed the seasonal variations in temperature and precipitation. The higher soil CO_2 emissions simulated on day 220 were consistent with the higher temperature and precipitation in this period. In the model, daily CO_2 emissions remained low during winter. At baseline temperature, the total annual CO_2 emissions was 6,384.69 kgC/hm^2, and the daily average CO_2 emission was 17.49 kgC/(hm^2·d). With variation in the baseline temperature from ±1°C to ±2°C, the soil CO_2 emissions increased.

With variation in the baseline temperature +2°C, it improved to 42.40% compared with the baseline temperature and it decreased to 37.38% with variation in the baseline temperature from –2°C. In this study, the precipitation was not a principal factor affecting soil CO_2 emissions, which had shown very little changes with the variation in the baseline precipitation from ±10% to ±20% (Table 1).

2.2.2 N_2O and NO emission

N_2O and NO emissions from soils are caused principally by microbial nitrification and denitrification (Li *et al.*,

Table 1 Simulated total annual greenhouse gases (GHGs) emissions from the soil of *Abies fabric* forest for the two simulation scenarios in comparison to emissions from baseline (%)

GHGs	Temperature					Precipitation				
	–2°C	–1°C	Baseline	+1°C	+2°C	80%	90%	Baseline	110%	120%
CO_2	62.62	80.23	100.00	120.81	142.40	99.71	99.70	100.00	100.14	100.31
N_2O	124.08	103.96	100.00	103.91	108.70	89.45	94.34	100.00	104.92	110.34
NO	80.18	86.67	100.00	114.20	128.18	89.67	95.54	100.00	103.93	107.25

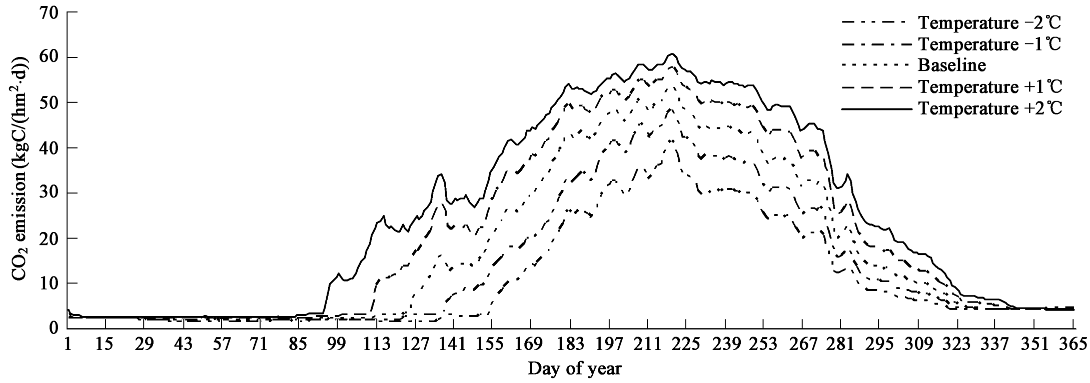

Fig. 5 Simulated soil CO_2 emissions from *Abies fabric* forest soil for variation in the baseline temperature from ±1°C to ±2°C.

2000). These processes are driven by environmental factor, temperature, moisture, substrate concentration, and so on. The changes of these factors will alter the magnitude and the pattern of N_2O and NO fluxes. With increased temperature and decreased baseline temperature, the total annual soil N_2O emissions all increased (Table 1). At baseline temperature varied +2°C the total annual soil N_2O emissions improved 8.70% compared with baseline temperature and improved 24.08% at baseline temperature varied −2°C. When temperature increased, the increased emission of N_2O maybe because of the improved denitrification, and when temperature decreased, it is because of the improved nitrification. Different from N_2O emissions with variation in the baseline temperature from ±1°C to ±2°C, the total annual soil NO emissions showed increased trend (Table 1). It showed that the effect of temperature changes on N-trace gas production was very complicated. The total annual soil NO emission improved 28.18% with variation in the baseline temperature of +2°C. At lower temperature due to lower N uptake rates by plants the availability of NH_4^+ for nitrification would increase, but soil NO emission was still reduced. The higher temperature will increase evapotranspiration and decrease soil moisture. It is unfavorable for denitrification but these could be compensated for by temperature effects on rates of soil N_2O and NO emissions by denitrification.

The results of soil N_2O and NO emissions with variation in the baseline precipitation from ±10% to ±20% are shown in Fig.6 and Table 1. The total annual N_2O and NO emissions with baseline precipitation were 0.57 and 0.21 kgN/hm^2, respectively. Precipitation has a major effect on biogeochemical cycling of nitrogen in forest soils. Changes in the amount of precipitation and its temporal distribution directly influence the soil moisture regime and, consequently, the water availability for plant production, and the soil microbial processes. With variation

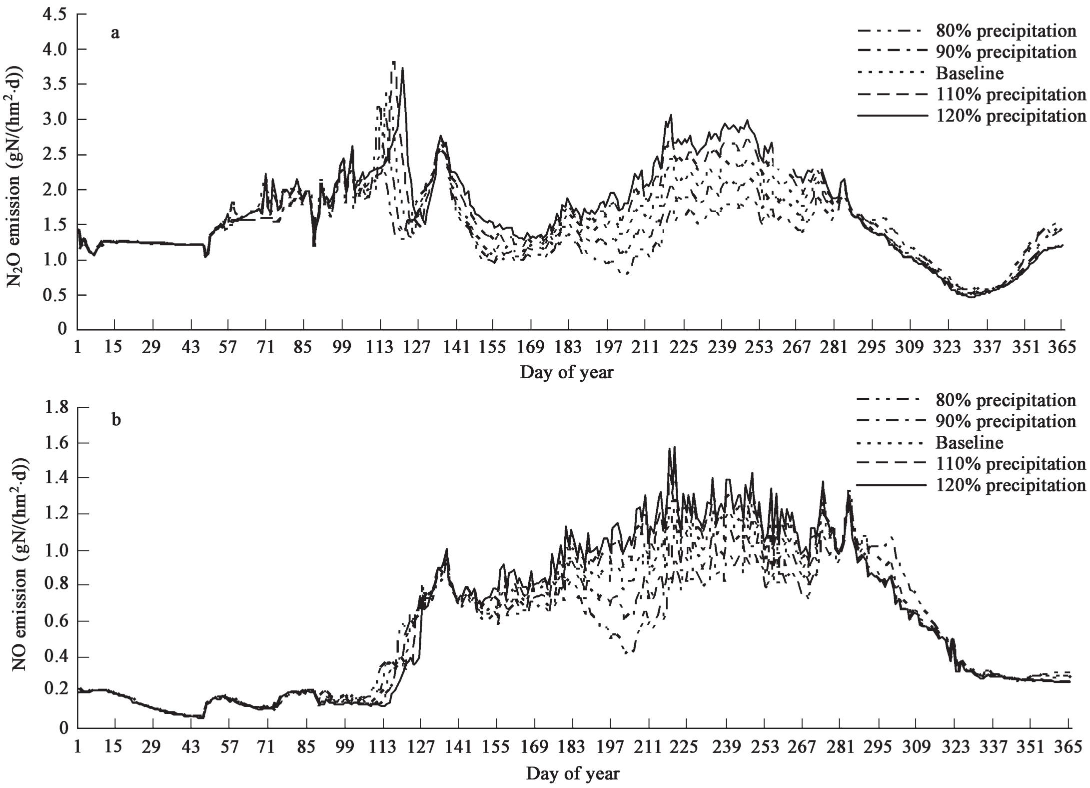

Fig. 6 Simulated soil N_2O (a) and NO (b) emissions from *Abies fabric* forest soil with variation in baseline precipitation from ±10% to ±20%.

in the baseline precipitation from ±10% to ±20%, the total annual N_2O and NO emissions showed increasing trends. Soil N_2O and NO emissions were sensitive to increasing precipitation in comparison with the baseline scenario: decreased 10.55% (N_2O) and 10.33% (NO) for a scenario with 20% lower precipitation rates, increased 10.34% (N_2O) and 7.25% (NO) for a scenario with 20% higher precipitation rates. Soil N_2O and NO emissions due to denitrification depended on the size of the "anaerobic balloon" (Li *et al*., 2000).

3 Conclusions

The process-oriented biogeochemical model, Forest-DNDC, was used to simulate the effects of climatic factors, temperature and precipitation changes on the carbon fluxes, soil carbon dynamics, soil CO_2, N_2O, and NO emissions of *A. fabric* forest of subalpine in the Gongga mountain. Results indicated that with variation in the baseline temperature from –2°C to +2°C, GPP showed apparent increasing trend, but NPP and NEP changed sightly. With increasing baseline precipitation, GPP and NPP slightly increased and the NEP showed decreasing trend because soil microbial respiration improved at higher precipitation rates. With increasing temperature, the annual changes of SOC increased, the humads and humus on forest floor changes little and on the mineral soil showed increasing trends. The annual changes of SOC and humads increased and the humus kept steadiness with variation in the baseline precipitation from ±10% to ±20%. Soil CO_2 emissions increased with the increase of temperature and CO_2 emissions changed little with increased baseline precipitation. With increased temperature and decreased baseline temperature, the total annual soil N_2O emissions all increased. And the total annual soil NO emissions increased with variation in the baseline temperature from −2°C to +2°C. The total annual N_2O and NO emissions increased with the increase of precipitation. In conclusion, temperature changes strongly affected carbon fluxes, soil carbon dynamics, and soil GHGs emissions. In this study, the precipitation was not a principal factor affecting carbon fluxes, soil carbon dynamics, and soil CO_2 emissions, but changes in precipitation could exert strong effect on soil N_2O and NO emissions.

Acknowledgements

This work was supported by the National Key Basic Research Program (973) of China (No. 2003CB415201). The authors thank Chen Binru, Luo Ji who provided data support for this study and the Forest-DNDC model that is available for free over the Internet at http://www.dndc.sr.unh.edu.

References

Brown L, Syed B, Jarvis S C, Sneath R W, Phillips V R, Goulding K E T, Li C, 2002. Development and application of a mechanistic model to estimate emission of nitrous oxide from UK agriculture. *Atmospheric Environment*, 36(6): 917–928.

Butterbach-Bahl K, Stange F, Papen H, Grell G, Li C S, 2000. Impact of changes in temperature and precipitation on N_2O and NO emissions from forest soils. In: Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (Van Ham J., Baede A. P. M., Meyer L. A., Ybema R., eds.). Netherlands: Kluwer Academic Publishers. 167–171.

Butterbach-Bahl K, Stange F, Papen H, Li C S, 2001. Regional inventory of nitric oxide and nitrous oxide emissions for forest soils of southeast Germany using the biogeochemical model PnET-N-DNDC. *Journal of Geophical Research*, 106: 34155–34166.

Butterbach-Bahl K, Kesik M, Miehle P, Papen H, Li C, 2004. Quantifying the regional source strength of N-trace gases across agricultural and forest ecosystems with process based models. *Plant and Soil*, 260: 311–329.

Cheng G W, Luo J, 2003. The carbon accumulation and dissipation features of sub-alpine woodland in Mt. Gongga. *Journal of Geographical Sciences*, 13: 13–18.

Cheng G W, Luo J, 2004. Succession features and dynamic simulation of sub-alpine forest in the Gongga Mountain, China. *Journal of Mountain Science*, 1: 29–37.

Cui J B, Li C S, Sun G, Trettin C, 2005a. Linkage of MIKE SHE to Wetland-DNDC for carbon budgeting and anaerobic biogeochemistry simulation. *Biogeochemistry*, 72: 147–167.

Cui J B, Li C S, Trettin C, 2005b. Analyzing the ecosystem carbon and hydrologic characteristics of forested wetland using a biogeochemical process model. *Global Change Biology*, 11: 278–289.

Cui J B, Li C S, Trettin C, 2005c. Modeling biogeochemistry and forest management practices for assessing GHGs mitigation strategies in forested wetlands. *Environmental Modeling and Assessment*, 10: 43–53.

Dong Y S, Qi Y C, Luo J, Liang T, Luo K L, Zhang S, 2003. Experimental study on N_2O and CH_4 fluxes from the dark coniferous forest zone soil of the Gongga Mountain, China. *Science in China (Series D)*, 46: 285–295.

IPCC (Intergovernmental Panel on Climate Change), 2001. Climate Change 2001: The Scientific Basis. Contribution of working Group I to The Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton J. T., Ding Y., Griggs D. J., Noguer M., van der Linden P. J., Dai X., Maskell K., Johnson C. A., eds.). Cambridge: Cambridge University Press. pp881.

Kesik M, Ambus P, Baritz R, Brggemann N, Butterbach-Bahl K, Damm M, Duyzer J, Horváth L, Kiese R, Kitzler B, Leip A, Li C, Pihlatie M, Pilegaard K, Seufert G, Simpson D, Skiba U, Smiatek G, Vesala T, Zechmeister-Boltenstern S, 2005. Inventories of N_2O and NO emissions from European forest soils. *Biogeosciences*, 2: 353–375.

Kesik M, Brggemann N, Forkel R, Kiese R, Knoche R, Li C S, Seufert G, Simpson D, Butterbach-Bahl K, 2006. Future scenarios of N_2O and NO emissions from European forest soils. *Journal of Geophysical Research*, 111: 2018–2022.

Kiese R, Li C S, Hilbert D W, Papen H, Butterbach-Bahl K, 2005. Regional application of PnET-N-DNDC for estimating the N_2O source strength of tropical rainforests in the wet tropics of Australia. *Global Change Biology*, 11: 128–144.

Li C S, Frolking S, Frolking T A, 1992a. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *Journal of Geophysical Research*, 97: 9759–9776.

Li C S, Frolking S, Frolking T A, 1992b. A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications. *Journal of Geophysical Research*, 97: 9777–9783.

Li C S, Cui J B, Sun G, Trettin C, 2004. Modeling impacts of management on carbon sequestration and trace gas emissions in forested wetland ecosystems. *Environmental Management*, 33: 176–186.

Li C S, Aber J, Stange F, Butterbach-Bahl K, Papen H, 2000. A processs-oriented model of N_2O and NO emissions from forest soils: 1. model development. *Journal of Geophysical Research*, 105(D4): 4369–4384.

Li C S, Frolking S, Butterbach-Bahl K, 2005. Carbon sequeatration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Climatic Change*, 72: 321–328.

Miehle P, Livesley S J, Li C S, Feikema P M, Adams M A, Arndt S K, 2006a. Quantifying uncertainty from large-scale model predictions of forest carbon dynamics. *Global Change Biology*, 12: 1421–1434.

Miehle P, Livesley S J, Feikemab P M, Li C, Arndt S K, 2006b. Assessing productivity and carbon sequestration capacity of *Eucalyptus globulus* plantations using the process model Forest-DNDC: Calibration and validation. *Ecological Modelling*, 192: 83–94.

Smith P, Smith J U, Powlson D S, McGill W B, Arah J R M, Chertov O G, Coleman K, Franko U, Frolking S, Jenkinson D S, Jensen L S, Kelly R H, Klein-Gunnewiek H, Komarov A, Li C, Molina J A E, Mueller T, Parton W J, Thornley J H M, Whitmore A P, 1997. A comparison of the performance of nine soil organic matter models using seven long-term experimental datasets. *Geoderma*, 81: 153– 225.

Smith W N, Desjardins R L, Grant B, Li C, Lemke R, Rochette P, Corre M D, Pennock D, 2002. Testing the DNDC model using N_2O emissions at two experimental sites in Canada. *Canadian Journal of Soil Science*, 82: 365–374.

Stange F, Butterbach-Bahl K, Papen H, Zechmeister-Boltenstern S, Li C, Aber J, 2000. A process-oriented model of N_2O and NO emissions from forest soils: 2. Sensitivity analysis and validation. *Journal of Geophysical Research*, 105(D4): 4385–4398.

Wang L, Ouyang H, Peng K, Tian Y Q, Zhang F, 2004. Distribution characteristics of SOM and nitrogen on the eastern slope of Goonga Mountain. *Journal of Geographical Sciences*, 14(4): 481–487.

Wang L, Ouyang H, Zhou C P, Zhang F, Song M H, Tian Y Q, 2005. Soil organic matter dynamics along in the Gongga Mountain on a vertical vegetation gradient the Tibetan Plateau. *Journal of Integrative Plant Biology*, 47(4): 411–420.

Zhang B H, He Y R, Zhou H Y, Cheng G W, 2003. The features of soil aggregation and its eco-environmental effects under different subalpine forests on the east slope of Gongga Mountain, China. *Journal of Forestry Research*, l4(1): 80–82.

Zhang Y, Li C S, Trettin C, Li H, Sun G, 2002. An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems. *Global Biogeochemical Cycles*, 16: 1–17.