Soil Ecol. Lett. 2020, 2(1): 73–82
https://doi.org/10.1007/s42832-020-0021-y

SEL Soil Ecology Letters

RESEARCH ARTICLE

Predicting plant–soil N cycling and soil N_2O emissions in a Chinese old-growth temperate forest under global changes: uncertainty and implications

Weiwei Dai[1,2,3], Edith Bai[1,4,*], Wei Li[5], Ping Jiang[1], Guanhua Dai[6], Xingbo Zheng[6]

1 CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
2 College of Land Resource and Environment, Jiangxi Agricultural University, Nanchang 330045, China
3 Key laboratory of Poyang Lake Watershed Agricultural Resources and Ecology of Jiangxi Province, Nanchang 330045, China
4 School of Geographical Sciences, Northeast Normal University, Changchun 130024, China
5 College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
6 Research Station of Changbai Mountain Forest Ecosystems, Chinese Academy of Sciences, Erdaobaihe 133600, China

ARTICLE INFO

Article history:
Received August 12, 2019
Revised December 24, 2019
Accepted January 7, 2020

Keywords:
Global change
DayCent
Denitrification
Nitrification
Soil N_2O emission
Temperate forest

ABSTRACT

Soil-emitted N_2O contributes to two-thirds of global N_2O emissions, and is sensitive to global change. We used DayCent model to simulate major plant–soil N cycling processes under different global change scenarios in a typical temperate mixed forest in north-eastern China. Simulated scenarios included warming (T), elevated atmospheric CO_2 concentration ([CO_2]) (C), increased N deposition (N) and precipitation (P), and their full factorial combinations. The responses of plant–soil nitrogen cycling processes including net N mineralization, plant N uptake, gross nitrification, denitrification and soil N_2O emission were examined. Concurrent increase of elevated [CO_2] and N deposition displayed most strong interactive effects on most fluxes. Using the results from experimental studies for evaluation, simulation uncertainty was highest under elevated [CO_2] and increased precipitation among the four global change factors. N deposition had a fundamental impact on soil N cycle and N_2O emission in our studied forest. Despite forest soil acting as a N sink for added N, scenarios which included increased N deposition showed higher cumulative soil N_2O emissions (summed up from 2001 to 2100). In particular, the scenario which included T, P, and N had the largest cumulative soil N_2O emission, which was a 24.4% increase over that under ambient conditions. Our study points to the importance of the interactive effects of global change factors on plant–soil N cycling and the necessity of multi-factor manipulation experiments.

1 Introduction

N_2O is a potent and persistent greenhouse gas (IPCC 2001), and also an important stratospheric ozone depleting substance (Ravishankara et al., 2009). Soil currently contributes to approximately two-thirds of global N_2O emissions (Thom-

* Corresponding author
E-mail address: baie612@nenu.edu.cn (E. Bai)

son et al., 2012), mainly through nitrification and denitrification. Both processes are controlled by soil microbes and mediated by many factors, including soil aeration status, soil moisture, availability of labile C, soil NH_4^+ and NO_3^- concnetration, among others (Barnard et al., 2005). Global change brings physical, chemical, and biological changes to the plant–soil ecosystem. It may have a profound impact on soil N_2O emissions via affecting plant–soil N cycling processes (Brown et al., 2012).

Warming may affect temperature-dependent microbial processes (Peterjohn et al., 1994), decrease soil oxygen by increasing soil respiration (Barnard et al., 2005), deplete soil labile C by increasing microbial activity (Butler et al., 2012), and decrease soil moisture (Bai et al., 2013). Increased precipitation may affect soil moisture, soil aeration status, wet N deposition, labile C concentration in soil solution, and leaching of NO_3^- and organic N (Hall et al., 2013). Elevated atmospheric CO_2 concentration may increase labile C input via increased litter-fall and fine-root production (Bader and Korner 2010), affect plant N uptake (Finzi et al., 2007), increase soil moisture by improving plant water use efficiency (Battipaglia et al., 2013), and create anoxic micro-sites through increased heterotrophic consumption of O_2 (Wieder et al., 2011). Increased N deposition provides external NO_3^-, NH_4^+, and organic N to the soil (Lu et al., 2011) and may also cause soil acidification (Magill et al., 2000).

Depending on site characteristics, a single global change factor may have positive, no effect, or negative effect on soil N_2O emissions. Combination of multiple global change factors further increases the complexities. The high set-up and maintenance cost precludes long-term study of the forest-soil system in response to all possible global changes through manipulation experiments. To understand the effect of global change it is helpful to use model simulation as a first step, and examine those processes which we had preliminary theoretical and empirical understanding.

This study used a process-based biogeochemical model, DayCent, to simulate plant–soil N cycling processes under various global change scenarios in an old-growth temperate mixed forest, typical for north-eastern China. DayCent is a well-established model to simulate plant–soil C-N cycling, including soil N_2O emissions (Parton et al., 2001). Temperate forests are usually thought to be N-limited, and could be a potential N sink for increasing anthropogenic N inputs. It is therefore important to investigate how global changes may affect plant–soil N cycling processes and if global change will attenuate or accelerate N_2O leaking from the plant–soil system. We aim to present a systematic image on the response of the plant–soil system to possible global changes, identify potentially important global change factors and the interactions to guide future experimental work, and to provide a scientific basis for policy making.

2 Methods

2.1 DayCent model

DayCent model simulates key plant–soil N cycling processes and estimates soil N_2O fluxes emitted from nitrification and denitrification. N mineralization is regulated by microbial respiration and the C:N ratios of soil organic matter pools. Plant N uptake is dependent upon the root biomass and available mineral N (Metherell et al., 1993). Nitrification is modeled as a function of soil NH_4^+-N concentration, water-filled pore space, temperature, pH, and texture, while denitrification is a function of soil NO_3^--N concentration, water-filled pore space, heterotrophic respiration, and texture (Parton et al., 2001). DayCent simulates soil N_2O emissions based on the hole-in-the-pipe model of Firestone and Davidson (1989). The N_2O fluxes emitted from nitrification and denitrification are proportional to the rates of corresponding processes.

2.2 Study site and simulation scenarios

Our study site locates in the Changbai Mountain National Nature Reserve (127°38′ E, 41°42′ N). Dominant tree species include *Pinuskoraiensis*, *Acer mono*, *Tiliaamurensis*, *Fraxinusmandschurica*, and *Quercusmongolica*. Mean annual temperature is 2.1°C and the growing season spans from May to September. Annual precipitation is 745 mm, 85% of which falling in the growing season. It has a dark brown soil developed from volcanic ash (Albic Luvisol). The top 10 cm soil has a pH of 5.48, with sand and clay taking up 19% and 32%, respectively.

Daily weather data from 1958 to 2012 were collected to drive DayCent. The model was run under ambient condition for over 1000 years to bring the model into equilibrium, and then global changes were simulated from 2013 to 2100.The global changes were set based on the projections of IPCC (2007) and Galloway et al. (2004). Specifically, air temperature gradually increased 3.3°C (T), annual precipitation gradually increased 9% (P), atmospheric [CO_2] gradually increased from 350 p.p.m. to 700 p.p.m.(C). N deposition gradually increased from current rate of 23.6 kg N ha^{-1} yr^{-1} (Wang et al., 2012) to 50 kg N ha^{-1} yr^{-1} in 2050, and stayed at 50 kg N ha^{-1} yr^{-1} from 2051 to 2100 (N). Sixteen scenarios were simulated, including ambient condition and a complete combination of four projected global changes. These scenarios enabled us to examine four main effects related to each factor, six two-way interactive effects, four three-way interactive effects, and one four-way interactive effect.

2.3 Model calibration

To get reliable simulation results, DayCent was calibrated using soil water content, net primary production (NPP), heterotrophic respiration (Rh), soil organic C (SOC), soil organic N (SON), soil NH_4^+-N and NO_3^--N concentrations, and N_2O emissions as suggested by Del Grosso et al. (2011).

Figure 1 showed the measured and modeled volumetric soil water content at different depths (data were reported as mean±standard deviation). Soils were collected every 5 days from May to Sep. 2003 (Yang et al., 2006). Calibration of other variables was reported in Table 1. Soil characteristics are spatially and even seasonally heterogeneous. Therefore data from different sources were collected to calculate the mean and standard deviation of each variable either as a long-term average or a mean value measured by different methods in order to reduce the bias brought by single observation and avoid overfitting. NPP value was obtained both from the dendrometry method (Zhao, 2005) and from the calculation of GPP. According to Wang et al. (2006), the ratio of NPP/GPP was 0.48 in the study area, where GPP was obtained both from the eddy covariance technique (Zhang et al., 2006) and the chamber-based measurements (Wang et al., 2009). Rh were calculated as the difference between ecosystem respiration (Re) and autotrophic respiration (Ra), where Re was obtained both from the eddy covariance technique (Zhang et al., 2006) and the chamber-based measurements (Wang et al., 2009) and Ra was calculated as 0.52 × GPP (Wang et al., 2006). Soil N_2O fluxes were measured using the closed chamber method in both studies (Xiao et al., 2004; Bai et al., 2014). The total flux during the measurement was calculated based on the average hourly emission rate. Personal measurements in 2015 (unpublished) were also used to get a reliable range of soil SOC, SON, NH_4^+-N, and NO_3^--N concentrations.

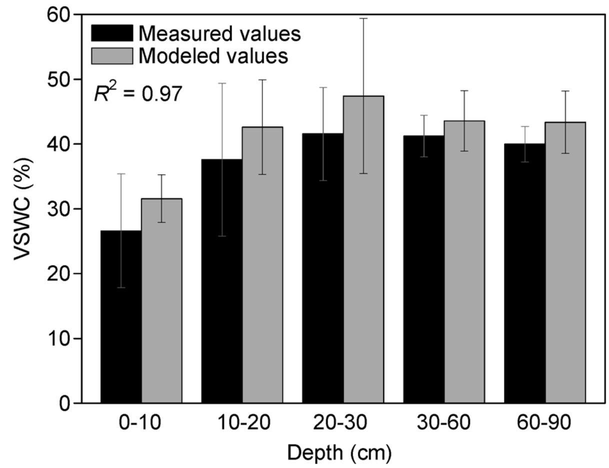

Fig. 1 Validation of volumetric soil water content (VSWC) at different depths.

3 Results

For each scenario, all reported fluxes were averaged from 2091 to 2100 in order to reduce the impact of temporal variations. The percent change of a given flux between each global change scenario and the ambient condition was calculated. Calculation of the relative main and interactive effects of global change factors was in the same way as that in Luo et al. (2008). Briefly, for each global change factor (e.g., warming), its relative main effect on a given flux (e.g., N_2O emission) was calculated as: 100% × (N_2O_T − $N_2O_{Ambient}$)/$N_2O_{Ambient}$. For scenarios with multiple global change factors (e.g., warming and increased precipitation, termed as

Table 1 Calibration of DayCent model

Variable	Time	Modeled value	Observed value	Sources
NPP ($g\ C\ m^{-2}\ yr^{-1}$)	2003	696	695±190	Zhao 2005; Wang et al., 2006; Zhang et al., 2006; Wang et al., 2009
Rh ($g\ C\ m^{-2}\ yr^{-1}$)	2003	570	504±165	Wang et al., 2006; Zhang et al., 2006; Wang et al., 2009
0–20 cm SOC ($g\ C\ m^{-2}$)	2003–2015	13617.39 ±94.09	13827.72 ±1074.61	Shao et al., 2006; Zhang et al., 2009; Wang and Yang 2010; personal unpublished data, 2015
0–20 cm SON ($g\ N\ m^{-2}$)	2005–2015	953.51 ±3.41	1018.18 ±139.52	Zhang et al., 2009; Han, 2012; personal unpublished data, 2015
0–15 cm soil NH_4^+-N ($mg\ kg^{-1}$)	2007–2015	9.33±1.78	6.99±5.31	Hu et al., 2009; Xu et al., 2010; Luo et al., 2012; Bai et al., 2014; personal unpublished data, 2015
0–10 cm soil NO_3^--N ($mg\ kg^{-1}$)	2007–2015	5.69±2.25	6.65±11.38	Hu et al., 2009; Xu et al., 2010; Luo et al., 2012; Bai et al., 2014; personal unpublished data, 2015
Soil N_2O emission ($g\ N\ m^{-2}$)	Jul. – Oct., 2012	0.15	0.18±0.18	Bai et al., 2014
	Sep. 2002–Oct. 2003	0.36	0.44	Xiao et al., 2004

scenario T × P), its relative effect was calculated as 100% × ($N_2O_{T \times P} - N_2O_{Ambient}$)/ $N_2O_{Ambient}$, and its relative interactive effect was calculated as: 100% × [($N_2O_{T \times P} - N_2O_{Ambient}$) − ($N_2O_T$ -$N_2O_{Ambient}$) − (N_2O_P −$N_2O_{Ambient}$)] / $N_2O_{Ambient}$.

3.1 Net N mineralization and plant uptake of N

Net N mineralization was stimulated in all scenarios (Fig. 2A). For single global change factor, increased atmospheric [CO_2] had the most stimulation on net N mineralization (+ 12.3%), followed by warming (+ 10.4%), increased N deposition (+ 7.6%), and increased precipitation (+ 4.9%) (Table 2). Scenarios with multiple global change factors generally had higher net N mineralization rates, though their interactive effects were generally small. Scenario P × N × C had the largest positive interactive effect (+ 5.9%) on net N mineralization, and scenario N × C had the largest negative interactive effect (–6.7%) (Table 2).

Plant N uptake increased in most scenarios, except for scenario P × C (–3.6%), scenario C (–2.8%) and scenario N (–0.1%) (Fig. 2B). For single global change factor, warming had the most positive effect on plant N uptake (+ 6.8%), while elevated [CO_2] had a small but negative effect (–2.8%) (Table 2). Scenario N × C had the most positive interactive effect (+ 3.6%), while scenario P × C had the most negative interactive effect (–1.5%) (Table 2).

3.2 Gross nitrification, denitrification and soil N_2O emission

Gross nitrification was reduced in scenario P × C (–18.5%), scenario C (–16.6%), scenario T × P × C (–3.3%) and scenario T × C (–2.7%), and was stimulated in other scenarios (Fig. 2C). For single global change factor, increased N deposition and warming both gave large stimulation to gross nitrification (+ 31.3% and + 14.1%, respectively), while increased atmospheric [CO_2] had a moderate negative effect (–16.6%). Scenario P × N × C had the most positive interactive effect on gross nitrification (+ 5.6%), while scenario P × N has the most negative interactive effect (–5.3%) (Table 2).

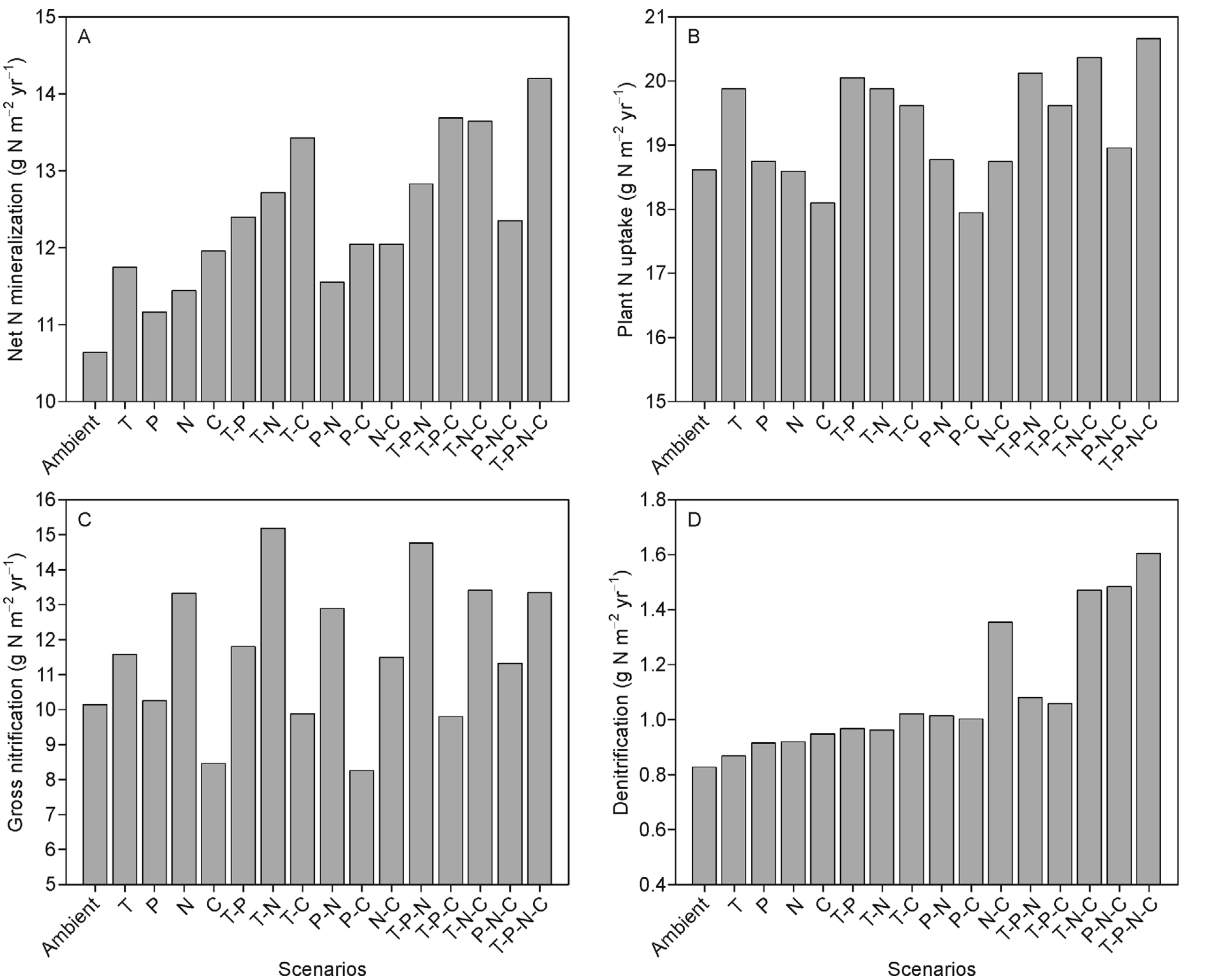

Fig. 2 Major N processes in simulated scenarios. (A) mineralization, (B) plant N take, (C) gross nitrification, (D) denitrification.

Table 2 Relative main and interactive effects of major fluxes in simulated scenarios

Scenarios	Net min.	N uptake	Gross nit.	Denit.	Soil N_2O
Relative main effect (%)					
T	10.4	6.8	14.1	4.8	–0.6
P	4.9	0.7	1.1	10.6	5.7
N	7.6	–0.1	31.3	11.0	30.2
C	12.3	–2.8	–16.6	14.5	–14.4
Relative interactive effects (%)					
T × P	1.2	0.2	1.0	1.5	–1.5
T × N	1.6	0.1	4.1	0.5	3.2
T × C	3.5	1.3	–0.2	4.0	–0.9
P × N	–3.9	0.3	–5.3	0.9	–1.5
P × C	–4.0	–1.5	–3.0	–4.0	0.0
N × C	–6.7	3.6	–1.4	38.0	15.3
T × P × N	–1.2	0.1	–0.9	1.3	–0.9
T × P × C	0.4	0.6	0.2	–3.6	–1.5
T × N × C	–0.4	0.5	0.9	4.7	0.6
P × N × C	5.9	1.7	5.6	8.3	–0.6
T × P × N × C	1.9	–0.5	0.6	1.4	1.0

Denitrification was calculated as the sum of denitrification-derived N_2 and N_2O fluxes. Denitrification flux was increased in all global change scenarios (Fig. 2D). For single global change factor, increased atmospheric [CO_2] had the largest positive impact on denitrification (+14.5%), followed by increased N deposition (+11.0%). Scenario N × C had the most positive interactive effect on denitrification (+38.0%), while scenario P × C had the most negative interactive effect (–4.0%) (Table 2).

Soil N_2O emission was greatly stimulated in scenarios which include increased N deposition (+ 30.2%–34.8%), and was reduced in scenarios C (–14.4%), T × C (–15.9%), P × C (–8.7%), T × P × C (–13.1%)(Fig. 3). For single global change factor, N deposition gave the largest stimulation to soil N_2O emission (+ 30.2%), while increased atmospheric [CO_2] had a moderate negative effect (–14.4%). Scenario N × C had the most positive interactive effect (+ 15.3%), and the interactive effect in other scenarios were generally small (Table 2).

Considering the strong positive effect of N deposition on denitrification and soil N_2O emissions, we also calculated the ratio of denitrification:N deposition and the ratio of soil N_2O emission:N deposition (Fig. 4). In the simulated scenarios, the ratio of denitrification:N deposition ranged from 0.18 (Scenario N) to 0.45 (Scenario T × P × C), and scenarios which include increased N deposition generally had lower ratios. Similarly, for the ratio of soil N_2O emission: N deposition, scenarios with increased deposition generally had lower values (around 0.12) while the ratios in other scenarios ranged between 0.16 and 0.20.

4 Discussion

4.1 Main effects of global change on N fluxes

4.1.1 Net N mineralization

For increased N deposition and warming, modeled results of net N mineralization were consistent with existing experimental studies. Significant increase of net N mineralization was reported in hardwood forest after 9 years N addition (Magill et al., 2000). Meta-analysis revealed that experimental warming increased net N mineralization by 75.2% in forest ecosystems (Bai et al., 2013). Elevated [CO_2] was observed to stimulate N mineralization by Hofmockel et al. (2011), but had no significant effect (Zak et al., 2003; Finzi et al., 2006; Holmes et al., 2006) or even negative effect on net N mineralization in other studies (Hungate et al., 1999). Rainfall manipulation experiments relevant to plant–soil N fluxes are limited. The effect of increased precipitation on net N mineralization was highly dependent on season (Landesman and Dighton, 2010).

4.1.2 Plant N uptake

Simulated effects of warming on plant N uptake were consistent with existing experimental studies. Bai et al. (2013) found warming increased N concentration in tree leaves by 10.7% through meta-analysis. Contrary to the model prediction, elevated [CO_2] led to either significant increase (Finzi et al., 2007; Hofmockel et al., 2011) or no change (Hagedorn et al., 2000; Finzi et al., 2007) in plant N uptake as observed in several FACE (Free-Air Carbon dioxide Enrichment) and OTC (Open-Top Chamber) experiments. This discrepancy has been recognized by Finzi (2007) and Franklin (2009). DayCent assumes that elevated [CO_2] would stimulate photosynthesis and root growth, reduce stomatal conductance and photorespiration, decrease plant N concentration and increase N use efficiency in C3 species (Metherell et al., 1993). These assumptions were based on empirical studies before FACE experiments were conducted. The response of plant N uptake to increased N deposition is dependent on the changing biological and abiological factors. A long-term experiment at Harvard Forest observed an increase in plant N uptake after 9 years of N addition (Magill et al., 2000), followed by an unchange or even delince six years later (Magill et al., 2004). To our knowledge, there is no experimental work to investigate the effect of increased precipitation on forest N uptake. But we know soil moisture is important for plant N uptake, for example, when the soil is very dry, plant N uptake would be reduced due to inhibited diffusion (Landesman and Dighton, 2010).

4.1.3 Nitrification, denitrification and N_2O emissions

Due to the limited observations of gross nitrification in response to global changes, we included observations on net nitrification as an indirect evidence. Consistent with our modeling results, meta-analyses revealed that N addition significantly increased net nitrification and gross nitrification by 217% and 200% respectively (Barnard et al., 2005), and experimental warming significantly increased net nitrification by 32.2% (Bai et al., 2013). Decreased nitrification under elevated [CO_2] was inferred from a reduced recovery of nitrate in resin lysimeters in Florida scrub oak (Hungate et al., 1999). However, meta-analysis result claimed that elevated [CO_2] had no effect on gross nitrification based on four observations and increased net nitrification by 33% based on five observations (Barnard et al., 2005). In one study of ponderosa pine forests it was postulated that nitrification may decrease with increased precipitation (Hungate et al., 2007).

Available studies on denitrification mainly focused on N_2O emission because of the difficulty in measuring N_2 over background levels (Kulkarni et al., 2008). Denitrification contributed to 64.1% soil N_2O emission in our study area (Bai et al., 2014). Reduced moisture by warming generally has a negative effect on denitrification-derived N_2O and a positive effect on nitrification-derived N_2O (Bijoor et al., 2008). Our modeling result also showed this trend. Warming decreased denitrification-derived N_2O by 10.8% and increased nitrification-derived N_2O by 14.1% (Fig. 3). However, warming also caused a 12.1% increase in denitrification-derived N_2, therefore increased the denitrification rate. According to the model result, elevated [CO_2] decreased both denitrification-derived and nitrification-derived N_2O, but greatly increased denitrification-derived N_2, therefore increased the denitrification rate.

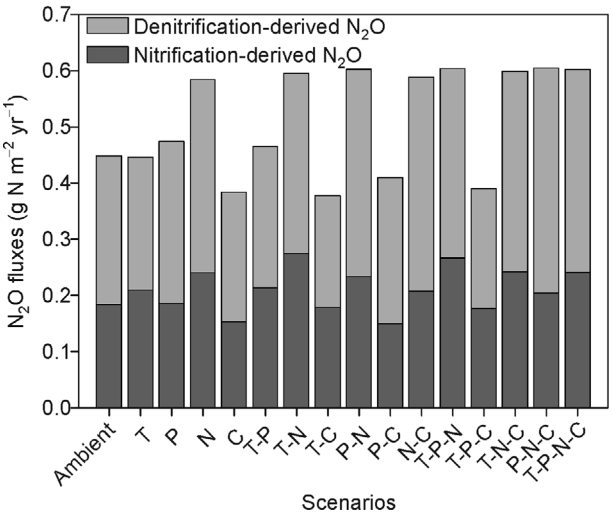

Fig. 3 Soil N_2O emission and its composition in simulated scenarios.

Model predicted a strong positive effect of increased N deposition on soil N_2O emission. Meta-analyses confirmed that N addition caused a 105% increase in soil N_2O efflux for forest ecosystems (Barnard et al., 2005), and a 216% increase across all ecosystems (Liu and Greaver 2009). Along an atmospheric N deposition gradient, soil N_2O fluxes were much higher at high N deposition sites (16 – 32 μg N_2O-N m^{-2} h^{-1}) than moderate N deposition sites (5 – 10 μg N_2O-N m^{-2} h^{-1}) in Scots pine forests (Butterbach-Bahl et al., 2002a). Warming had a marginal effect on soil N_2O emission according to our model prediction, also consistent with the meta-analysis result that warming had no significant effect on soil N_2O emission across all ecosystems (Bai et al., 2013). Model predicted a negative effect of elevated [CO_2] on soil N_2O emission while elevated [CO_2] was found to have no significant effect on soil N_2O emissions in temperate forests (Ambus and Robertson 1999; Hagedorn et al., 2000, Phillips et al., 2001). Very few field studies examined the effect of increased precipitation on soil N_2O emission in temperate forests while in tropical humid forest soil N_2O emission decreases with increasing precipitation (Holtgrieve et al., 2006; Hall et al., 2013).

4.2 Interactive-effects of global change

Concurrent increase of elevated [CO_2] and N deposition (scenario N $\times$ C) displayed most strong interactive effects on most fluxes as shown in Table 2. It had the most positive interactive effect on denitrification, soil N_2O emission and plant N uptake, and the most negative interactive effect on net N mineralization. However, in an OTC experiment Hagedorn et al. (2000) observed no significant interactive effect of elevated [CO_2] and increased N deposition on soil N_2O emission and plant N uptake. They believed that CO_2

enrichment decreased soil N availability in forest ecosystems and increased the capacity of ecosystems to retain N deposition. For scenarios with more than two global change factors, concurrent increase of precipitation, N deposition and [CO_2] (scenario P $\times$ N $\times$ C) had the most strong interactive effects on net mineralization, plant N uptake, gross nitrification and denitrification. Unfortunately, there is no other experimental data in forest ecosystems to validate these interactive effects.

4.3 Effects of N deposition

N deposition had a fundamental impact on soil N cycle and N_2O emission in our studied temperate forest. Two ratios were used to characterize the effect of N deposition on soil N cycle from different aspects. First, the ratio of soil N_2O emission:N deposition (kg N_2O-N ha^{-1} yr^{-1} per kg N deposition ha^{-1} yr^{-1}), also called N_2O emission factor. N_2O emission factor showed a wide range in forest ecosystems. Eickenscheidt et al. (2011) compiled its values for temperate forests, which ranged from < 0.001 to 0.22. Model estimated the emission factor was 0.19 under ambient condition, close to the upper bound of the reported range. In the scenarios which included increased N deposition, the emission factor dropped to 0.12, indicating a smaller fraction of N deposition escaped of the soil system in forms of N_2O and the buffering capacity of forest soil.

Second, the ratio of denitrification:N deposition. After N gets into the forest-soil system via deposition, it may finally enter water bodies via leaching or runoff or enter the atmosphere mainly in forms of N_2 and N_2O. Denitrification is an important N gaseous loss pathway, and may have a significant impact on atmospheric chemistry. Model estimated this ratio was 0.35 at ambient condition, ranging between 0.18 and 0.45 in all scenarios, and was generally low in scenarios which include increased N deposition. At the Höglwald Forest, the estimated ratio (N_2 + N_2O):N deposition was 0.41 for spruce site and 0.94 for beech site at a N deposition rate of 20 kg N ha^{-1} yr^{-1} (Butterbach-Bahl et al., 2002b). This ratio may serve as an upper bound for the ratio of denitrification:N deposition.

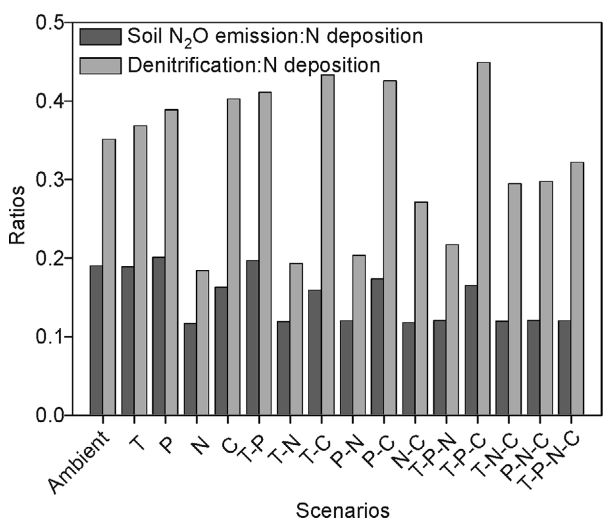

Fig. 4 N-deposition related indexes.

4.4 Projection of soil N_2O emissions and its implications

Given its residence time of over 100 years in the atmosphere (IPCC 2001), soil N_2O emissions were accumulated from 2001 to 2100 and mapped in Fig. 5. At ambient condition, the accumulated soil N_2O emission would reach 40.2 g N m^{-2} from 2000 to 2100. The lowest cumulative emission occurred in scenario C (38.5 g N m^{-2}), while the highest in scenario T $\times$ P $\times$ N (50.0 g N m^{-2}). It was interesting to find that in an annual grassland treatment with increased temperature, precipitation, and N addition also had the highest soil N_2O emission among 16 treatments, which were the same combinations of four global change factors as in our model simulation (Brown et al., 2012).

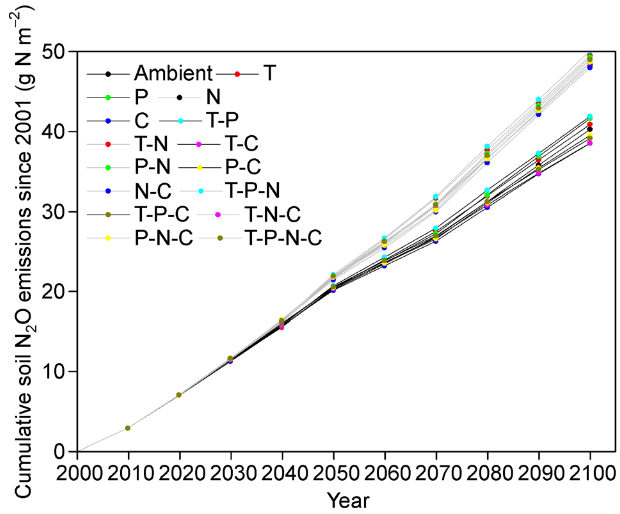

Fig. 5 Cumulative soil N_2O emissions from 2001 to 2100 in simulated scenarios.

As seen in Fig. 5, an obvious fork developed over the 100 years: the upper branch was comprised of eight scenarios which contained increased N deposition, and the rest scenarios belonged to the lower branch. The gap between these two branches was relatively small before 2050, and it became significantly larger over the second half of the 21st century. The sensitivity of soil N_2O emission to N deposition in the studied temperate forest suggested the positive feedback loop that promotes global warming. Although N-limited ecosystems such as our studied temperate forest can serve as a buffer for N deposition (Magill et al., 2000), their N_2O emissions will still increase, especially after years of continued elevated N deposition. As carbon sequestration and low carbon economy have become the hotspots in policy making, the model prediction that the largest cumulative soil N_2O emissions occurred in scenario T $\times$ P $\times$N highlighted the potential detriment of unrestrained reactive N emission (e.g., fertilizer application and motor vehicle emissions) when carbon emission is under control.

5 Conclusions

According to our modeling results, for single global change factor, N deposition caused a 30.2% increase in soil N_2O emission, increased precipitation increased soil N_2O emissions by 5.7%, while elevated [CO_2] caused a 14.4% decrease and warming had a small effect (–0.6%). When multiple global changes factors were simulated, soil N_2O emissions were greatly stimulated in scenarios that included increased N deposition. Concurrent increase of temperature, N deposition and precipitation induced the largest soil N_2O efflux. It was predicted that the accumulated soil N_2O emission from 2001 to 2100 would reach 50.0 g N m^{-2} in scenario T × P × N, which was a 24.4% increase over that in ambient condition.

Model estimation that both warming and elevated [CO_2] decreased denitrification-derived N_2O but increased the denitrification rate may point to an interesting direction for future experimental work. Simulation uncertainty for major nitrogen cycling processes was high under elevated [CO_2] and increased precipitation scenarios among the four global change factors due to inconsistent results in experimental studies or lack of experimental data. Further experimental studies are needed to investigate relevant mechanisms and improve model predictions. Based on the modeling results, we suggested that manipulation experiments of N addition and its interactions with other global change factors should be given high priority to study denitrification and soil N_2O emissions in temperate forests. Our study highlighted the importance of controlling reactive N production in tandem with decreasing carbon emission.

Acknowledgments

This study was supported by the National Basic Research Program of China (973 program; 2014CB954400) and the National Natural Science Foundation of China (41401289).

References

Ambus, P., Robertson, G.P., 1999. Fluxes of CH_4 and N_2O in aspen stands grown under ambient and twice-ambient CO_2. Plant and Soil 209,1–8.

Bader, M.K.F., Korner, C., 2010. No overall stimulation of soil respiration under mature deciduous forest trees after 7 years of CO_2 enrichment. Global Change Biology 16, 2830–2843.

Bai, E., Li, S., Xu, W., Li, W., Dai, W., Jiang, P., 2013. A meta-analysis of experimental warming effects on terrestrial nitrogen pools and dynamics. New Phytologist 199, 431–440.

Bai, E., Li, W., Li, S., Sun, J., Peng, B., Dai, W., Jiang, P., Han, S., 2014. Pulse increase of soil N_2O emission in response to N addition in a temperate forest on Mt Changbai, northeast China. PLoS One 9, e102765.

Barnard, R., Leadley, P.W., Hungate, B.A., 2005. Global change, nitrification, and denitrification: A review. Global Biogeochemical Cycles 19, GB1007

Battipaglia, G., Saurer, M., Cherubini, P., Calfapietra, C., McCarthy, H. R., Norby, R.J., Cotrufo, M.F., 2013. Elevated CO_2 increases tree-level intrinsic water use efficiency: insights from carbon and oxygen isotope analyses in tree rings across three forest FACE sites. New Phytologist 197, 544–554.

Bijoor, N.S., Czimczik, C.I., Pataki, D.E., Billings, S.A., 2008. Effects of temperature and fertilization on nitrogen cycling and community composition of an urban lawn. Global Change Biology 14, 2119–2131.

Brown, J.R., Blankinship, J.C., Niboyet, A., van Groenigen, K.J., Dijkstra, P., Le Roux, X., Leadley, P.W., Hungate, B.A., 2012. Effects of multiple global change treatments on soil N_2O fluxes. Biogeochemistry 109, 85–100.

Butler, S.M., Melillo, J.M., Johnson, J.E., Mohan, J., Steudler, P.A., Lux, H., Burrows, E., Smith, R.M., Vario, C.L., Scott, L., Hill, T.D., Aponte, N., Bowles, F., 2012. Soil warming alters nitrogen cycling in a New England forest: implications for ecosystem function and structure. Oecologia 168, 819–828.

Butterbach-Bahl, K., Breuer, L., Gasche, R., Willibald, G., Papen, H., 2002a. Exchange of trace gases between soils and the atmosphere in Scots pine forest ecosystems of the northeastern German lowlands: 1. Fluxes of N_2O, NO/NO_2 and CH_4 at forest sites with different N-deposition. Forest Ecology and Management 167, 123–134.

Butterbach-Bahl, K., Willibald, G., Papen, H., 2002b. Soil core method for direct simultaneous determination of N_2 and N_2O emissions from forest soils. Plant and Soil 240,105–116.

Del Grosso, S.J., Parton, W.J., Keough, C.A., Reyes-Fox, M., 2011. Special features of the DayCent modeling package and additional procedures for parameterization, calibration, validation, and applications. in: Ahuja, L.R., Ma, L., eds. Methods of introducing system models into agricultural research, Madison, WI, USA. PP. 155–176

Eickenscheidt, N., Brumme, R., Veldkamp, E., 2011. Direct contribution of nitrogen deposition to nitrous oxide emissions in a temperate beech and spruce forest- a ^{15}N tracer study. Biogeosciences 8, 621–635.

Finzi, A.C., Moore, D.J.P., DeLucia, E.H., Lichter, J., Hofmockel, K.S., Jackson, R.B., Kim, H.S., Matamala, R., McCarthy, H.R., Oren, R., Pippen, J.S., Schlesinger, W.H., 2006. Progressive nitrogen limitation of ecosystem processes under elevated CO_2 in a warm-temperate forest. Ecology 87, 15–25.

Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen, C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R., Schlesinger, W.H., Ceulemans, R., 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. Proceedings of the National Academy of Sciences of the United States of America 104, 14014–14019.

Firestone, M.K., Davidson, E.A., 1989. Microbial basis of NO and N_2O production and consumption in soils. in: Andreae, M.O., Schimol, D.S., eds. Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley, New York.PP. 7–21

Franklin, O., McMurtrie, R.E., Iversen, C.M., Crous, K.Y., Finzi, A.C., Tissue, D.T., Ellsworth, D.S., Oren, R., Norby, R.J., 2009. Forest fine-root production and nitrogen use under elevated CO_2: contrasting responses in evergreen and deciduous trees explained by a common principle. Global Change Biology 15, 132–144.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vorosmarty, C.J., 2004. Nitrogen cycles: past, present, and future. Biogeochemistry 70, 153–226.

Hagedorn, F., Bucher, J.B., Tarjan, D., Rusert, P., Bucher-Wallin, I., 2000. Responses of N fluxes and pools to elevated atmospheric CO_2 in model forest ecosystems with acidic and calcareous soils. Plant and Soil 224, 273–286.

Hall, S.J., McDowell, W.H., Silver, W.L., 2013. When wet gets wetter: Decoupling of moisture, redox biogeochemistry, and greenhouse gas fluxes in a humid tropical forest soil. Ecosystems 16, 576–589.

Han, S.J., ed., 2012. China Ecosystem Long-term Observation and Research Dataset: Changbai Mountain Station (in Chinese). Beijing: China Agriculture Press.

Hofmockel, K.S., Gallet-Budynek, A.,McCarthy, H.R., Currie, W.S., Jackson, R.B., Finzi, A.C., 2011. Sources of increased N uptake in forest trees growing under elevated CO_2: results of a large-scale 15N study. Global Change Biology 17, 3338–3350.

Holmes, W.E., Zak, D.R., Pregitzer, K.S., King, J.S., 2006. Elevated CO_2 and O_3 alter soil nitrogen transformations beneath trembling aspen, paper birch, and sugar maple. Ecosystems 9, 1354–1363.

Holtgrieve, G.W., Jewett, P.K., Matson, P.A., 2006. Variations in soil N cycling and trace gas emissions in wet tropical forests. Oecologia 146, 584–594.

Hu, Y.L., Han, S.J., Li, X.F., Zhao, Y.T., Li, D., 2009. Responses of soil available nitrogen of natural forest and secondary forest to simulated N deposition in Changbai Mountain. Dongbei Linye Daxue Xuebao, 37(5), 36–42 (in Chinese).

Hungate, B.A., Dijkstra, P., Johnson, D.W., Hinkle, C.R., Drake, B. G., 1999. Elevated CO_2 increases nitrogen fixation and decreases soil nitrogen mineralization in Florida scrub oak. Global Change Biology 5, 781–789.

Hungate, B.A., Hart, S.C., Selmants, P.C., Boyle, S.I., Gehring, C. A., 2007. Soil responses to management, increased precipitation, and added nitrogen in ponderosa pine forests. Ecological Applications 17, 1352–1365.

IPCC, 2001. Climate change 2001: The scientific basis. Cambridge University Press, Cambridge, UK.

IPCC, 2007. Climate change 2007: The physical science basis. Cambridge University Press, Cambridge, UK.

Kulkarni, M.V., Groffman, P.M., Yavitt, J.B., 2008. Solving the global nitrogen problem: it's a gas! Frontiers in Ecology and the Environment 6, 199–206.

Landesman, W.J., Dighton, J., 2010. Response of soil microbial communities and the production of plant-available nitrogen to a two-year rainfall manipulation in the New Jersey Pinelands. Soil Biology & Biochemistry 42, 1751–1758.

Liu, L.L., Greaver, T.L., 2009. A review of nitrogen enrichment effects on three biogenic GHGs: the CO_2 sink may be largely offset by stimulated N_2O and CH_4 emission. Ecology Letters 12, 1103–1117.

Lu, M., Yang, Y.H., Luo, Y.Q., Fang, C.M., Zhou, X.H., Chen, J.K., Yang, X., Li, B., 2011. Responses of ecosystem nitrogen cycle to nitrogen addition: a meta-analysis. New Phytologist 189, 1040–1050.

Luo, X.B., Zhang, Y.Q., Xu, H., Zheng, J.Q., 2012. Seasonal dynamics of soil active carbon and nitrogen pools in surface soil of temperate broad-leaved and Korean pine mixed forest. Journal of Ecology and Rural Environment 28, 42–46 (in Chinese).

Luo, Y., Gerten, D., Le Maire, G., Parton, W., Weng, E., Zhou, X., Keough, C., Beier, C., Ciais, P., Cramer, W., Dukes, J., Emmett, B., Hanson, P., Knapp, A., Linder, S., Nepstad, D., Rustad, L., 2008. Modeled interactive effects of precipitation, temperature, and [CO_2] on ecosystem carbon and water dynamics in different climatic zones. Global Change Biology 14, 1986–1999.

Magill, A.H., Aber, J.D., Berntson, G.M., McDowell, W.H., Nadelhoffer, K.J., Melillo, J.M., Steudler, P., 2000. Long-term nitrogen additions and nitrogen saturation in two temperate forests. Ecosystems 3, 238–253.

Magill, A.H., Aber, J.D., Currie, W.S., Nadelhoffer, K.J., Martin, M.E., McDowell, W.H., Melillo, J.M., Steudler, P., 2004. Ecosystem response to 15 years of chronic nitrogen additions at the Harvard Forest LTER, Massachusetts, USA. Forest Ecology and Management 196, 7–28.

Metherell, A.K., Harding, L.A., Cole, C.V., Parton, W.J., 1993. CENTURY: soil organic matter model environment. Technical documentation, agroecosystem version 4.0. GPSR Technical Report 4. USDA Agricultural Research Service, Fort Collins, Colorado, USA.

Parton, W.J., Holland, E.A., Del Grosso, S.J., Hartman, M.D., Martin, R.E., Mosier, A.R., Ojima, D.S., Schimel, D.S., 2001. Generalized model for NO_x and N_2O emissions from soils. Journal of Geophysical Research, D, Atmospheres 106, 17403–17419.

Peterjohn, W.T., Melillo, J.M., Steudler, P.A., Newkirk, K.M., Bowles, F.P., Aber, J.D., 1994. Responses of trace gas fluxes and N availability to experimentally elevated soil temperatures. Ecological Applications 4, 617–625.

Phillips, R.L., Whalen, S.C., Schlesinger, W.H., 2001. Influence of atmospheric CO_2 enrichment on nitrous oxide flux in a temperate forest ecosystem. Global Biogeochemical Cycles 15, 741–752.

Ravishankara, A.R., Daniel, J.S., Portmann, R.W., 2009. Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21_{st} century. Science 326, 123–125.

Shao, Y.H., Pan, J.J., Xu, X.W., Yang, L.X., 2006. Determination of forest soil organic carbon pool sizes and turnover rates in Changbaishan. Journal of Soil and Water Conservation 20, 99–102 (in Chinese).

Thomson, A.J., Giannopoulos, G., Pretty, J., Baggs, E.M., Richardson, D.J., 2012. Biological sources and sinks of nitrous oxide and strategies to mitigate emissions. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 367, 1157–1168.

Wang, B., Yang, X.S., 2010. Comparison of carbon content and carbon density of four typical zonal forest ecosystems. Hunan

Nongye Daxue Xuebao 36, 464–473 (in Chinese) (Natural Sciences) .

Wang, C., Han, S., Zhou, Y., Yan, C., Cheng, X., Zheng, X., Li, M.H., 2012. Responses of fine roots and soil N availability to short-term nitrogen fertilization in a broad-leaved Korean pine mixed forest in northeastern China. PLoS One 7, e31042.

Wang, M., Guan, D.X., Wang, Y.S., Hao, Z.Q., Liu, Y.Q., 2006. Estimate of productivity in ecosystem of the broad-leaved Korean pine mixed forest in Changbai Mountain. Science in China Series D-Earth Sciences 49, 74–88.

Wang, M., Guan, D.X., Han, S.J., Wu, J.L., 2009. Comparison of eddy covariance and chamber-based methods for measuring CO_2 flux in a temperate mixed forest. Tree Physiology 30, 149–163.

Wieder, W.R., Cleveland, C.C., Townsend, A.R., 2011. Throughfall exclusion and leaf litter addition drive higher rates of soil nitrous oxide emissions from a lowland wet tropical forest. Global Change Biology 17, 3195–3207.

Xiao, D.M., Wang, M., Wang, Y.S., Ji, L.Z., Han, S.J., 2004. Fluxes of soil carbon dioxide, nitrous oxide and firedamp in broadleaved Korean pine forest. Journal of Forestry Research 15, 107–112.

Xu, Y, Zhang, J.H., Han, S.J., Wang, S.T., Wang, C.G., Wang, S.Q., 2010. Spatial heterogeneity of soil inorganic nitrogen in a broad-leaved-Korean pine mixed forest in Changbai Mountains of northeast China. Ying Yong Sheng Tai Xue Bao 21, 1627–1634 (in Chinese).

Yang, H., Pei, T., Guan, D., Jin, C., Wang, A., 2006. Soil moisture dynamics under broad-leaved Korean pine forest in Changbai Mountains. Ying Yong Sheng Tai Xue Bao 17, 587–591.

Zak, D.R., Holmes, W.E., Finzi, A.C., Norby, R.J., Schlesinger, W. H., 2003. Soil nitrogen cycling under elevated CO_2: A synthesis of forest face experiments. Ecological Applications 13, 1508–1514.

Zhang, J.H., Yu, G.R., Han, S.J., Guan, D.X., Sun, X.M., 2006. Seasonal and annual variation of CO_2 flux above a broad-leaved Korean pine mixed forest. Science in China. Series D, Earth Sciences 49, 63–73.

Zhang, X.Y., Meng, X.J., Gao, L.P., Fan, J.J., Xu, L.J., 2009. Soil nutrient contents and their responses to the soil core transferring experiment of three typical natural forests along the Changbai Mountain transect. Ziran Ziyuan Xuebao 24, 1386–1392 (in Chinese).

Zhao, X.S., 2005. Estimation of net ecosystem productivity by eddy covariance and biometry in the mixed forest of broad-leaved and Korean-pine in Changbai Mountain. Master's Thesis, Chinese Academy of Sciences, Beijing, China.