Nitrogen deposition and its effect on carbon storage in Chinese forests during 1981–2010

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HIGHLIGHTS

- We developed a new algorithm to simulate the variation of nitrogen deposition.
- The N deposition rate has increased significantly, during 1981–2010 in China.
- An increase in C storage of Chinese forests attributed to increase of N deposition.
- The N use efficiency is the highest in the moderate N deposition.

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ABSTRACT

Human activities have resulted in dramatically increased nitrogen (N) deposition worldwide, which is closely linked to the carbon (C)-cycle processes and is considered to facilitate terrestrial C sinks. In this study, we firstly estimated the spatial and temporal variations of N deposition during 1981–2010 based on a new algorithm; then we used a newly improved process-based ecosystem model, CEVSA2, to examine the effects of N deposition on C storage in Chinese forests. The results show that the rate of N deposition increased by $0.058 \text{ g N m}^{-2} \text{ yr}^{-1}$ between 1981 and 2010. The N deposition rate in 2010 was $2.32 \text{ g N m}^{-2} \text{ yr}^{-1}$, representing a large spatial variation from 0 to $0.25 \text{ g N m}^{-2} \text{ yr}^{-1}$ on the northwestern Qinghai–Tibet Plateau to over $4.5 \text{ g N m}^{-2} \text{ yr}^{-1}$ in the southeastern China. The model simulations suggest that N deposition induced a 4.78% increase in the total C storage in Chinese forests, most of which accumulated in vegetation. C storage increased together with the increase in N deposition, in both space and time. However, N use efficiency was highest when N deposition was $0.4\text{--}1.0 \text{ g N m}^{-2} \text{ yr}^{-1}$. We suggest conducting more manipulation experiments and observations in different vegetation types, which will be greatly helpful to incorporate additional processes and mechanisms into the ecosystem modeling. Further development of ecosystem models and identification of C–N interactions will be important for determining the effects of N input on C cycles on both regional and global scales.

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1. Introduction

Forest ecosystems, especially in the northern hemisphere and

high-latitude regions, are the sinks for “missing C” (IPCC, 2007). These sinks might result from nitrogen (N) deposition (Townsend et al., 1996; Schimel et al., 2001), as well as forest growth, CO_2 fertilization, and climate change. It has been estimated that global N deposition in 1990 was about three times that in 1860 (Dentener et al., 2006). The average annual rate of N deposition in China increased to 21.1 kg ha^{-1} in the 2000s (Liu et al., 2013), which even exceeded the rates in Europe and the United States (Lu and Tian, 2007). At present, the regional (Lu et al., 2012a; Liu et al., 2013; Jia et al., 2014) and global N deposition estimations (Dentener

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et al., 2006) are usually derived from observations and simulations using atmospheric chemical transfer models; while ecosystem models require a simple and applicable algorithm to estimate and predict regional and global N deposition patterns.

Many research efforts have focused on the response of C storage to N deposition (Schindler and Bayley, 1993; Hudson et al., 1994; Townsend et al., 1996). The NITREX project in Europe is the first international program to examine the effects and critical loads of N deposition (Wright and Rasmussen, 1998), and other chronic N-amendment experiments are being carried out around the world (Aber and Magill, 2004). Previous observations and experiments on the influence of N deposition on C-cycle processes have shown varying effects, including increases, decreases, or unchanged (Bowden et al., 2004), and complex interactions with other factors (Aber et al., 1989, 1998). These studies suggest that the impact of N deposition on C storage in forests is still unclear. Recent research in China has concentrated on the short-term responses of C-cycle processes to the addition of N (Fan et al., 2004; Li et al., 2005; Cao et al., 2006; Fan et al., 2007; Duan et al., 2009). However, these observations and experiments are scattered across country and N-associated processes and underlying mechanisms have not been well investigated.

These long-term N-addition experiments help us to identify C–N interactions and coupling relationships, providing both a theoretical foundation for improving mechanistic ecosystems models and an important method of evaluating and predicting the effects of N deposition on the C cycle on large scales and over long time periods. The discrepancies between model simulations and observations also provide information for future experiments. Current ecosystem models have shown that N deposition may stimulate C sequestration on both regional (Lu et al., 2012a; Lu et al., 2012b; Wei et al., 2012) and global scales (Xu–Ri and Prentice, 2008; Jain et al., 2009). Townsend et al. (1996) suggested that the increase in the C sink induced by N deposition was about 25% of the total global C sink. Some studies have focused on Chinese terrestrial ecosystems (Tian et al., 2011), especially forest ecosystems, however the responses of different forest types to various N deposition rates still remain unclear. Ecosystem models differ in model structures, assumptions, and parameterization, so they can show large differences in their estimates in the effect of N deposition on carbon cycle. Increased numbers of model simulations should lead to a profound understanding of the response of ecosystems to N deposition and clarify the existing uncertainties.

In this study, we developed a new algorithm to estimate the spatial and temporal variations of N deposition. Then, we used an improved process-based model, CEVSA2 (Carbon Exchange between Vegetation, Soil, and Atmosphere), to investigate the impact of N deposition on C storage and N use efficiency (NUE) in Chinese forest ecosystems, and to identify the different responses of various regions to N deposition during 1981–2010.

2. Methodology

2.1. Model description

2.1.1. General description

The CEVSA is a process-based biogeochemical model that simulates energy transfer, and water, C, and N cycles among the soil, vegetation, and the atmosphere. In the CEVSA2, three integral, independent, but interconnected cycles are examined: C, water, and N (Gu et al., 2010). The CEVSA2 includes major interactions between C and N, such as the effects of N on photosynthesis, respiration, carbon allocation, and soil C decomposition (Fig. 1).

The N controls on the C cycle in the CEVSA2 model are as follows.

Fig. 1. A schematic representation of the CEVSA2 model. The solid lines represent C, N, and water flows, and the dashed lines represent the interactions between C, N, and water cycles.

- (1) *Nitrogen uptake rate and control of photosynthesis and respiration.* Plant N uptake is dependent on the soil C and N contents and temperature (Woodward et al., 1995). The total N uptake is allocated to the leaf layers of the canopy, and is proportional to the mean irradiance on the leaves (Woodward et al., 1995). The leaf N content determines the maximum photosynthetic rate (Woodward et al., 1995), and leaf maintenance respiration and the dark respiration rate depend on the N uptake and temperature (Harley et al., 1992).
- (2) *Nitrogen controls on C allocation.* Sharpe and Rykiel (1991) proposed a generic relationship between the allocation of C to a given plant compartment and the availability of a particular resource (Friedlingstein et al., 1999). Based on this generic relationship, the CEVSA2 model considers the effects of water, N, and light availability on C allocation.
- (3) *Soil C:N ratio and soil total N content.* Soil N mineralization and transformation are simulated simultaneously with soil C decomposition. Consequently, the soil C:N ratios for all pools are expressed as a function of the soil C and N contents. The total soil available N includes the mineralized N from the active pool of organic matter, the amount of N added as fertilizer, and the N deposition.
- (4) *Soil N control of soil organic matter decomposition.* During the decomposition of organic matter, the decomposing microorganisms require released N, so that N availability and the C:N ratio affect the specific decay rate coefficients for carbon transformation between pools and decomposition. The CEVSA2 model estimates the balance between the potential need and supply of N.

2.2. Input data

2.2.1. Climate, land cover, CO₂ concentration, and soil data

The National Meteorological Information Center of China supplied all the meteorological datasets, including 10-day observational data from all 756 meteorological stations in China during the period 1954–2010. The station observation data were interpolated

at a spatial resolution of $0.1^\circ \times 0.1^\circ$ using ANUSPLINE (Hutchinson, 1989). The annual atmospheric CO_2 concentrations were from the NOAA Mauna Loa CO_2 dataset (<http://co2now.org/Current-CO2/CO2-Now/noaa-mauna-loa-co2-data.html>). The soil texture datasets were based on the 1:14,000,000 soil texture map of China. The land cover maps were derived from the Global Land Cover 2000 database (<http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php>).

2.2.2. N deposition data

Total inorganic N (TN) deposition includes the N in ammonium ($\text{NH}_4\text{-N}$) and the N in nitrate ($\text{NO}_3\text{-N}$) deposited into terrestrial ecosystems by precipitation (wet deposition) and dust (dry deposition). $\text{NH}_4\text{-N}$ is derived mainly from agriculture fertilization and intensive livestock farming (Davidson, 2009), and $\text{NO}_3\text{-N}$ from industrial and automotive combustion (Dentener et al., 2006). Jia et al. (2014) found a strong relationship between N deposition and precipitation, N fertilizer use, and fuel consumption. These three factors contribute to about 79% of the spatial divergence in N deposition. With reference to the method of Lin et al. (2000), we developed an algorithm to simulate the temporal and spatial variations in N deposition (N_{depo}) based on the relationships among N deposition, precipitation, N fertilizer use, and fuel consumption, as follows:

$$N_{\text{depo}} = \text{Amm}_{\text{depo}} + \text{Nit}_{\text{depo}} \quad (1)$$

$$\text{Amm}_{\text{depo}} = \text{PRE} \times P_1 \times \text{fert} + P_2 \times \text{fert} \quad (2)$$

$$\text{Nit}_{\text{depo}} = \text{PRE} \times P_3 \times \text{ener} + P_4 \times \text{ener} \quad (3)$$

where Amm_{depo} is deposition as $\text{NH}_4\text{-N}$, Nit_{depo} is deposition as $\text{NO}_3\text{-N}$, PRE is precipitation (mm), fert is N fertilizer use (g N m^{-2}), ener is fuel consumption (g coal m^{-2}), and P_1 , P_2 , P_3 , and P_4 are fitting parameters which can be related to fuel and fertilizer use efficiency. We collected 588 N deposition observational data from 163 sites to fit all the parameters. The data on county-level N fertilizer use and province-level energy consumption for 1978–2010 were obtained from the National Bureau of Statistics of China (NBS, <http://www.stats.gov.cn/>). The N fertilizer use and fuel consumption during 1961–1977 was extrapolated based on the trends in these two factors during 1978–1990.

2.3. Model simulation and validation

2.3.1. Model simulation

The CEVSA2 model was run at a spatial resolution of $0.1^\circ \times 0.1^\circ$ latitude by longitude. First, we used mean climate during 1961–2010 and 1960 atmospheric CO_2 concentration data to run the model until the C pools reached the equilibrium state. Then a transient simulation was performed using the climate data, atmospheric CO_2 , N fertilization, and N deposition during 1961–2010. We also set up two simulation experiments, with (Exp. 1) and without N deposition (Exp. 2), to identify the effect of N deposition on C sequestration by Chinese forests during 1961–2010. In this study, we only focus on the period of 1981–2010, when the N deposition increased obviously.

2.3.2. Model validation

We collected a range of observational data from literature (Jia et al., 2014; Zhu et al., 2014, 224 data, total and wet N deposition) to validate the model. It shows that the model can catch the temporal and spatial variations in N deposition in Chinese terrestrial ecosystems ($R^2 = 0.85$, $p < 0.001$) (Fig. 2). Our estimates are also

consistent with those of other researchers in China (Table 1).

Currently, manipulation experiments examining the effects of N addition on soil C storage are rare and scattered throughout China. Here, we validated the model simulations using long-term fertilizer experiments conducted at the Gongzhuling (Peng et al., 2004) and Hailun (Sui et al., 2005) observation and experimental stations in northeastern China. The fertilizer experiments were conducted from 1990 to 2002 at Gongzhuling and from 1985 to 2003 at Hailun. The sampling depth of the soil organic matter was 20 cm at both stations.

The soil organic C density in 100 cm profile was calculated as follows:

$$\text{SOC} = \text{SOM} \times 0.58 \times H \times B / 100, \quad (4)$$

where SOC is the soil organic C density (kg C m^{-2}), SOM is the soil organic matter at a depth of 20 cm (g kg^{-1}), 0.58 is the Bemmelen index, H is the depth, and B is the soil bulk density (g cm^{-3}). We calculated the differences between the N fertilizer input and the control treatments to validate the model. We conducted the model simulation with the same addition of N fertilizer at both sites, and included normal N deposition. We calibrated all the parameters and initial inputs against observations at the two sites.

The average change in soil C storage induced by the N addition at Gongzhuling station was $0.177 \text{ kg C m}^{-2}$ in the experiment and as compared to $0.204 \text{ kg C m}^{-2}$ in the CEVSA2 simulation, with relative error of 15.39%. The average change at Hailun was $0.300 \text{ kg C m}^{-2}$ in the experiment, slightly higher than the CEVSA2 simulation ($0.280 \text{ kg C m}^{-2}$), with relative error of 6.84%. The simulated relative changes in the soil organic C storage and the trends were comparable with those in the experiments (Fig. 3). The spatial heterogeneity of the soil properties resulted in intra-class variances (0.017 in Gongzhuling and 0.010 in Hailun) that were larger than the inter-class variances (0.003 in Gongzhuling and 0.009 in Hailun). The model did not include the complex relationships between N fertilizer and other factors or the pulse effect of the fertilizer, which may contribute to the discrepancy between the simulated and experimental results.

2.4. Calculation of NUE of nitrogen deposition

In this study, we analyzed the changes in NUE of deposited N over time and space. NUE of N deposition refers to the increase in

Fig. 2. Comparison between the CEVSA2 model simulations and observational data collected from literature.

Table 1
The average values and increased rates of N deposition in China during 1981–2010 for this study compared with those in other studies.

N deposition ($\text{gNm}^{-2} \text{yr}^{-1}$)			Increase rate ($\text{gNm}^{-2} \text{yr}^{-1}$)	Sources
1981–2010	1990s	2000s		
1.71		2.11	0.041	Liu et al., 2013
	1.11	1.39		Jia et al., 2014
		1.88	0.019	Tian et al., 2011; Lu et al., 2012a
1.12	1.06	1.71	0.058	This study

Fig. 3. Comparisons of the simulated responses of soil C storage increments with long-term fertilizer application experiments conducted on maize crops at (a) Hailun, and (b) Gongzhuling, in northeastern China.

total C storage by vegetation, soil, or litterfall divided by the increase in N deposition.

$$NUE_{\text{vege}} = \frac{\Delta \text{vegeC}}{\Delta N_{\text{dep}}} \quad (5)$$

$$NUE_{\text{soil}} = \frac{\Delta \text{soilC}}{\Delta N_{\text{dep}}} \quad (6)$$

$$NUE_{\text{litterfall}} = \frac{\Delta \text{litterfallC}}{\Delta N_{\text{dep}}} \quad (7)$$

$$NUE_{\text{total}} = \frac{\Delta \text{totalC}}{\Delta N_{\text{dep}}} \quad (8)$$

where, NUE_{vege} , NUE_{soil} , $NUE_{\text{litterfall}}$, and NUE_{total} mean vegetation, soil, litterfall, and total NUE by N deposition, respectively. ΔvegeC , ΔsoilC , $\Delta \text{litterfallC}$, and ΔtotalC indicate the changes in vegetation, soil, and litterfall C, respectively, attributable to N deposition during the past 30 years. ΔN_{dep} indicates the change in N deposition from 1981 to 2010.

3. Results and discussion

3.1. Temporal and spatial patterns of N deposition in China

Our results indicates that the N deposition rate increased significantly (about five-fold), during 1981–2010 (Fig. 4). The average N deposition rate was $1.13 \text{ g N m}^{-2} \text{ yr}^{-1}$, increasing from 0.46 to $2.32 \text{ g N m}^{-2} \text{ yr}^{-1}$. The increase in total N deposition was dominated by an increase in NHx-N deposition, which was about four times the NOy-N deposition rate. The total N deposition in Chinese forests in the past 30 years was 0.97 Pg N (10^{15} g N).

The N deposition rate displayed large spatial variations in China

(Fig. 5a–d). The highest wet, dry, and total N deposition rates were found in North, Central, and Southwest, and part of Northeast; while the lowest values occurred in Northwest, on Qinghai–Tibet Plateau, and parts of Inner Mongolia.

The spatial patterns of N deposition from this study are consistent with other observations (Jia et al., 2014) and model simulations (Dentener et al., 2006; Lu et al., 2012a; Lu et al., 2012b). Previous studies has suggested that nitrogen deposition is strongly influenced by human activities and is significantly related to the distance from big cities, N fertilizer use, and fuel consumption (Jia et al., 2014). During wet deposition, N enters ecosystems with rainfall, so wet deposition has a strong linear relationship with precipitation. Precipitation, N fertilizer use, fuel consumption, economic development, and the prevalence of big cities all influence N deposition; all these factors display declining trends from the southeast to the northwest of China.

Fig. 4. The interannual variations of N deposition in China during 1981–2010.

Fig. 5. The spatial patterns of (a) wet, (b) dry, and (c) total N deposition in China during 1981–2010; (d) shows eco-regions across China.

N is deposited in the soil continuously and could exceed the N uptake capacity of the ecosystem, leading to N saturation (Aber et al., 1989). Schulze et al. (1989) proposed the theory of the N-

saturation critical load, which is defined as the largest amount of N in the ecosystem that does not damage the ecosystem structure or function. Many studies have shown that the N-saturation critical

Table 2

Changes in forest carbon (C) storage in response to nitrogen (N) deposition in China during 1981–2010.

		Δ Vegetation C ($\text{gCm}^{-2} \text{yr}^{-1}$, %)	Δ Soil C ($\text{gCm}^{-2} \text{yr}^{-1}$, %)	Δ Litter C ($\text{gCm}^{-2} \text{yr}^{-1}$, %)	Δ Total C ($\text{gCm}^{-2} \text{yr}^{-1}$, %)	NUE_{vege} ($\text{gCg}^{-1} \text{N}$)	NUE_{soil} ($\text{gCg}^{-1} \text{N}$)	$\text{NUE}_{\text{total}}$ ($\text{gCg}^{-1} \text{N}$)	Ndep (gNm^{-2})
Decade	1980s	78(0.77)	35(0.45)	5(0.73)	118(1.95)	5.46	9.91	12.98	0.60
	1990s	138(1.37)	67(0.74)	9(0.96)	214(3.07)	3.38	5.93	11.76	1.06
	2000s	224(2.26)	116(0.78)	15(1.74)	355(4.78)	1.54	2.31	8.74	1.71
	2000s	224(2.26)	116(0.78)	15(1.74)	355(4.78)	1.54	2.31	8.74	1.71
Vegetation type	Broadleaved evergreen	149(0.24)	127(0.07)	9(0.25)	285(0.56)	9.87	8.21	18.67	1.74
	Broadleaved deciduous	62(1.03)	56(0.37)	5(1.03)	123(2.43)	4.46	3.44	8.24	1.38
	Needle-leaved evergreen	155(1.39)	136(0.92)	9(1.39)	300(3.70)	9.01	7.20	16.76	1.89
	Needle-leaved deciduous	12(1.22)	6(0.86)	0.4(1.22)	18.4(3.30)	5.06	2.46	7.67	0.24
	Mixed leaf type	2(1.18)	19(0.85)	2(1.18)	23(3.21)	0.84	9.27	10.95	0.33
N deposition (g N m^{-2})	0–0.4	11.10(1.06)	9.19(0.63)	0.74(1.06)	21.03(2.75)	6.35	4.65	11.40	0.21
	0.4–1.0	33.64(1.03)	28.93(0.55)	2.19(1.03)	64.76(2.61)	9.74	8.38	18.74	0.48
	1.0–3.0	128.69(1.01)	103.43(0.51)	9.21(1.01)	241.33(2.53)	5.70	2.75	8.86	2.28
	>3.0	233.37(1.12)	218.31(0.68)	16.02(1.12)	467.70(2.92)	4.84	3.31	8.63	3.19

Fig. 6. The spatial patterns of carbon (C) storage change in (a) vegetation, (b) soil, and (c) litterfall.

loads in terrestrial ecosystems range from 1.0 to 2.0 g N m⁻² yr⁻¹ (Duan et al., 2001; Bouwman et al., 2002; Holland et al., 2005). In the 2000s, the areas in which the N deposition rate was above 1.0 g N m⁻² yr⁻¹ or 2.0 g N m⁻² yr⁻¹ accounted for 37% or 34% of land surface, respectively. Zhang et al. (2012) showed that 35% of the total area has an N deposition rate above 1.0 g N m⁻² yr⁻¹ in the United States. This indicates that China has a more serious potential risk of N saturation than USA. This excess N may greatly affect the ecosystems and humans society (Aber et al., 1989, 1998). However, the N-saturation critical loads in ecosystems are still far from clear because of differences in environments, direct changes within ecosystems, and changes in land use and land cover.

3.2. Effect of N deposition on C storage in forests at a national level

Our simulated results suggest that forest C storage increased by 0.70 Pg C in response to the elevated N deposition in China during

1981–2010. The C storage kept increasing even when the N deposition rate was above 1–2 g N m⁻² yr⁻¹ (Table 2). This results is supported by some existing modeling studies, (Aber and Driscoll, 1997; Lu et al., 2012a; Lu et al., 2012b), although the estimated C changes differ among models due to different retention values (Aber and Driscoll, 1997). However, N addition experiments showed divergent results in different ecosystems (Neff et al., 2002; Magill et al., 2004; Pregitzer et al., 2008).

The simulation show that NUE was highest when N deposition was 0.4–1.0 g N m⁻² yr⁻¹ and decreased when N deposition was above 1.0 g N m⁻² yr⁻¹ (Table 2). Finzi et al. (2007) has shown that plants absorb more N instead of increasing their NUE, resulting in increased productivity with N deposition and elevated CO₂ concentrations. Observations and model simulations suggest that NUE varies widely, depending on the fate of the N deposited ranging from 7 to 177 g C g⁻¹ N (De Vries et al., 2009). Our simulations showed that the total C sequestration was 13.34 g C g⁻¹ N in

Fig. 7. The spatial patterns of NUE of (a) vegetation, (b) soil and (c) total carbon storage.

response to N deposition, lower than the estimates of other models (De Vries et al., 2009), but is closer to the experimental results.

Our results show that increases in vegetation carbon were larger than those in soil (Table 2). The increase in net primary productivity and the more C allocation to the woody biomass during N deposition cause more significant storage of C in vegetation (Janssens and Luyssaert, 2009). The C input into soil as litterfall increased because productivity increased. Meanwhile, the C loss as soil heterotrophic respiration increased because the soil available N supply increased. The increase of soil C storage was due to greater C input than C loss. In fact, many researchers have reported the negative effect of N on decomposition (Berg and Meentemeyer, 2002; Bowden et al., 2004; Mo et al., 2008; Janssens et al., 2010), and this contributes to increased soil C storage. The reduction of decomposition may be explained by decreases in the C allocated to root system, changes in the soil microbial community, and shifts in the stabilization of soil organic matter (Janssens et al., 2010).

In the present study, different forest types responded to N deposition differently (Table 2). Evergreen needle-leaved forests

had the largest N deposition and the largest increase in C storage. However, evergreen broadleaved forest had the highest NUE. Aber et al. (2003) demonstrated that N addition negatively affects plant growth and mortality in evergreen forests but not in deciduous stands in all European and American experiments. However, underlying mechanisms of these findings are still unclear.

3.3. Spatial variations in C changes in response to the N deposition

Our simulated results suggest that the spatial pattern of increased C storage was consistent with the N deposition (Fig. 6). The central and south areas of China had the greatest N deposition and the largest increase in C storage. The large areas of young planted forests in southern China showed a large increase in productivity in response to added N (Oren et al., 2001). Furthermore, N may promote the growth of plants in southern China, where other resources, such as heat and water, are not limited. The northeast and southwest parts of China, the two most important forested areas, are also the most important C sink regions. However, the

increases in C storage in these two regions were much lower than in other regions.

The highest NUE appeared in Southwest, northern South, and southern Central China, whereas parts of Northeast and southern South had relatively lower NUE (Fig. 7). Differences in forest types, N deposition rates, and soil N contents influenced the spatial differences in NUE. Deciduous needle-leaved, broad-leaved, and mixed leaf forests, mainly distributed in Northeast, had relatively lower NUE. N deposition in Northeast forest areas was also low, although the soil N content was high. In contrast, Southwest, northern South, and southern Central regions have large areas of evergreen needle-leaved and broad-leaved forests, which had the highest NUE of all the forest types. All these areas displayed medium N deposition.

3.4. Uncertainties and future research

The uncertainties in this study mainly involve the following two factors:

(1) The model does not represent all the known mechanisms and processes identified from observations and experiments. The negative effect of N on decomposition is commonly observed (e.g., Janssens et al., 2010), and it explains the increase in soil C storage induced by N deposition (Berg and Meentemeyer, 2002). Other indirect effects of N deposition, such as soil acidity, imbalance of cations, iron toxicity, and changes in plant communities (Berntson et al., 1998; Magill et al., 2004), are not included in the CEVSA2.

(2) Many processes and mechanisms that occur in C and N cycles, and their relationships under elevated rates of N deposition, remain unknown, which therefore brings uncertainties to the simulated results. Although long-term N deposition leads to N saturation in temperate forests (Aber et al., 1989, 1998), the critical load of N saturation for different ecosystems remains unknown. N leaching could be a quantitative index, with which to characterize N saturation (Aber et al., 1989), but N leaching is variable under different hydrological conditions in different regions. Little is known about the fate of N after it is deposited, and NUE is variable and dependent on the fate of N (Janssens and Luyssaert, 2009). This makes it difficult to quantify the effects of N deposition.

Moreover, it is necessary to consider why the growth and mortality of different types of forest vary in response to N deposition (Aber et al., 1998). The nonlinear response of photosynthesis to leaf N is affected by the species and the availability of other nutrients.

In addition, the responses of carbon cycle to the interactions between N with other factors differ greatly from single-factor responses (Duan et al., 2009). More observations and experiments are encouraged to be conducted to identify more processes and mechanisms controlling the interactions between the C and N cycles, which will be helpful to improve the accuracy of model simulations and predictions.

4. Conclusion

In this study, we used the CEVSA2 model to estimate N deposition and to investigate its effects on C storage in Chinese forests during 1981–2010. The simulations reveal that the N deposition rate had increased from 0.46 to 2.32 g N m⁻² yr⁻¹ in the past 30 years, which was dominated by an increase in NH_x-N deposition.

During the study period, forest C storage increased by 0.70 Pg C in response to the N deposited, but NUE shows a decreasing trend. The spatial pattern of C storage increase was consistent with the spatial pattern of N deposition, which both decreased from the southeast to the northwest of China. This indicates that more attention should be paid to N saturation and the different responses

in various forest types in ecosystem experiments and modeling to better represent the spatial heterogeneity of forest responses to N deposition.

To predict the effects of N input on the C cycle with ecosystem models, more effort is expected to concentrate on identifying the nonlinear C–N relationships and the interactions among C cycling, N cycling, and other factors.

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