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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 g N m^{-2} yr^{-1} between 1981 and 2010. The N deposition rate in 2010 was 2.32 g N m^{-2} yr^{-1}, representing a large spatial variation from 0 to 0.25 g N m^{-2} yr^{-1} on the northwestern Qinghai–Tibet Plateau to over 4.5 g N m^{-2} 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 0.4–1.0 g N m^{-2} 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.

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.

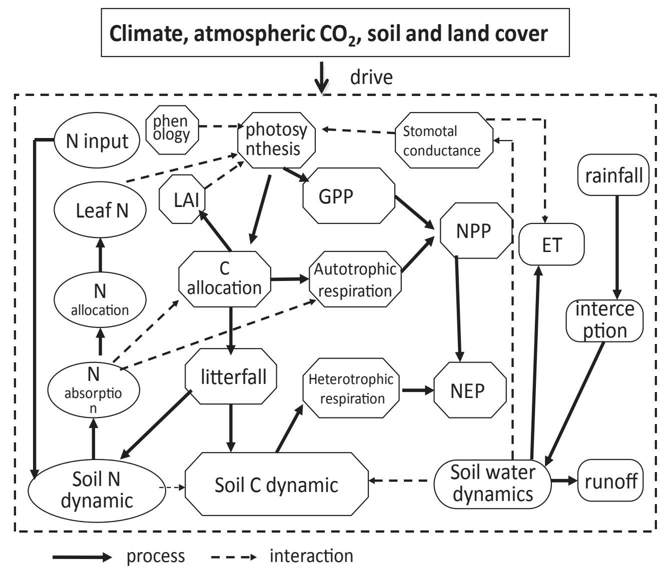

Fig. 1. A schematic representation of the CEVSA2 model. The solid lines represent C, N, and water flows, and the dashed lines represent the interactions between C, N, and water cycles.

(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, CO_2 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