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Effects of nitrogen deposition on carbon cycle in terrestrial ecosystems of China: A meta-analysis

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ABSTRACT

Nitrogen (N) deposition in China has increased greatly, but the general impact of elevated N deposition on carbon (C) dynamics in Chinese terrestrial ecosystems is not well documented. In this study we used a meta-analysis method to compile 88 studies on the effects of N deposition C cycling on Chinese terrestrial ecosystems. Our results showed that N addition did not change soil C pools but increased above-ground plant C pool. A large decrease in below-ground plant C pool was observed. Our result also showed that the impacts of N addition on ecosystem C dynamics depend on ecosystem type and rate of N addition. Overall, our findings suggest that 1) decreased below-ground plant C pool may limit long-term soil C sequestration; and 2) it is better to treat N-rich and N-limited ecosystems differently in modeling effects of N deposition on ecosystem C cycle.

1. Introduction

Global atmospheric nitrogen (N) deposition has dramatically increased due to extensive use of fossil fuels in industries and transportation, heavy application of fertilizers in agriculture, and expansion of animal husbandry (Galloway et al., 2004). Elevated N deposition is likely to change global carbon (C) cycles (Chapin et al., 2009) because N and C cycles are interdependent forming the basis of biogeochemical cycles and energy flows. A number of simulated field studies have been conducted in the past decades to investigate the effects of N deposition on ecosystem C cycles (Hogberg et al., 2006; Hyvonen et al., 2008; Pregitzer et al., 2008). Several meta-analysis studies have synthesized the available information to determine how ecosystem C pools and processes respond to N deposition at a global scale (LeBauer and Treseder, 2008; Lu et al., 2011; Xia and Wan, 2008). These studies have greatly improved our understanding regarding consequences of N deposition on C cycling and indicated a strong regional diversity in the response of ecosystem C to N deposition at a global scale.

China, the second-largest world economy, has undergone rapid economic development with an average annual GDP growth of 9.1 percent during 1989–2014 (NBSC, 2014). This rapid development has caused serious environmental issues. The latest data show that China contributed 29% of the total 36 billion tonnes carbon emitted from all human sources in 2013 (Friedlingstein et al., 2014). N deposition in China has also been among the greatest globally (Liu et al., 2013). The averaged N deposition rate in China has increased from 13.2 kg N ha^{-1} in the 1980s to 21.1 kg N ha^{-1} in the 2000s and is projected to increase in the coming decades (Liu et al., 2013). On the other hand, China also has experienced regionally distinct land-use histories and climate trends (Piao et al., 2009). Hence the degree of N deposition and its potential effects on the C cycle in

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Chinese terrestrial ecosystems should be different and are of increasing global concern due to the increasing interest in regional aspects of the global C cycle (Piao et al., 2009). Several N deposition monitoring programs and increased N deposition simulation experiments have been conducted since the late 1990s (Mo et al., 2006; Niu et al., 2010; Tu et al., 2010; Xu et al., 2009). Liu et al. (2011) recently presented a description of the effects of N deposition on ecosystem C cycling in China. However, a synthetic analysis of N deposition impacts on C dynamics in Chinese terrestrial ecosystems remains lacking.

In the present study, we used a meta-analysis technique to synthesize all the available information in China. Our main objectives were to: (1) quantify the responses of C fluxes (C influx and efflux) and C pool sizes (including plant, litter, microbe, soil, and dissolved organic C) to experimental N addition; (2) examine whether ecosystem types, fertilization rates and fertilization forms influence the responses of ecosystem C fluxes and pools to N addition; and (3) reveal the shortage of the current N deposition research in China. Our study provides valuable information to environmental policy- and decision-makers in their attempts to curb N emissions to the atmosphere, and to evaluate the effects of N deposition on terrestrial ecosystems.

2. Materials and methods

2.1. Data collection

Publications that studied C cycle response to N addition (Supplementary Information Table S2) were selected by searching Web of Science (2000–2013) and China National Knowledge Infrastructure (CNKI). In addition, unpublished data from some studies known to us were collected. To avoid publication biases, the following four criteria were applied to select appropriate studies: (1) the study must contain at least one of our selected variables with a clear record of the ecosystem type, N application rate, N fertilization form, and experimental duration; (2) the N addition and control plots started with the same climatic, soil and vegetation conditions to reduce effects of confounding factors; (3) the means, standard deviations or standard errors and sample sizes of the target variables were directly reported or could be either calculated from data presented in the paper or extracted using Origin 8.0 software (Origin Lab Corporation, Northampton, MA, USA) if the data were graphically presented; (4) the study must not use N deposition gradients as in several other studies (Fang et al., 2011; Huang et al., 2012). Most of the studies used one-time measurement, but latest samplings were used if more than one measurements at different temporal scales were available for the same experiment (Liu and Greaver, 2009; Treseder, 2008). Measurements for different N application rates were considered as independent observations if more than one levels of N addition were applied in the same experiment (Liu and Greaver, 2009).

The compiled database contained 12 variables associated with ecosystem C cycle, including C fluxes (i.e., net photosynthesis rate (NPR), net primary productivity (NPP), litterfall, litter decomposition rate (mass loss or [*k*] value), soil respiration, and ecosystem respiration), ecosystem C pools in above- and below-ground plant biomass, microbial biomass (MBC), dissolved organic C (DOC), organic horizon (OH) and mineral soil C. Data on C fluxes were obtained from studies where these data were directly reported. We used ecosystem respiration to replace soil respiration in grasslands because soil respiration is less measured in grasslands. Above- and below-ground plant C pools were determined by above-ground plant biomass or below-ground root biomass. Soil C pools were determined by soil C content or C storage. In addition, four supporting variables (i.e., soil inorganic N, leaf N, and soil pH) were evaluated (Supplementary Information Table S3) to explain the results of the main variables above.

All the variables were compared among different ecosystem types, N addition forms, and N addition rates. Four ecosystem types (i.e. N-rich subtropical forests, N-limited subtropical forests, temperate forests and grasslands) were identified. These ecosystems were categorized into two main groups as N-rich and N-limited ecosystem based on their initial soil N level and information on plant growth response to experimental N addition. That is, the old-growth subtropical forests (Mo et al., 2008) and forests dominated by N-fixing species (tree age > 30 years) (Zhang et al., 2012) were grouped into N-rich ecosystems as they have high soil N concentrations (Fang et al., 2008) and plant growth in these ecosystems is not limited by N availability (Lu et al., 2010). Early successional forests (Mo et al., 2007; Tu et al., 2010), temperate forests and grasslands, were grouped into N-limited ecosystem because they have low soil N level and plant growth in these ecosystems is limited by N availability. N addition levels were classified into three classes, including low N (LN; $\leq 60\ \text{kg N ha}^{-1}\ \text{yr}^{-1}$), medium N (MN; $61\text{–}120\ \text{kg N ha}^{-1}\ \text{yr}^{-1}$), and high N (HN; $> 120\ \text{kg N ha}^{-1}\ \text{yr}^{-1}$). In addition, we compared the variables only between two N fertilizer forms; NH_4NO_3 and urea which were the main fertilization forms in recent China's N deposition simulated experiments.

2.2. Analysis of data

The data were analyzed using meta-analysis method as described in Hedges et al. (1999). The effects of N addition on terrestrial ecosystem C pools and fluxes were estimated by response ratio (RR), which was calculated as:

$$\mathrm{RR} = \ln\left(\overline{X_t}/\overline{X_c}\right) = \ln\left(\overline{X_t}\right) - \ln\left(\overline{X_c}\right) \tag{1}$$

where $(\overline{X_t})$ and $(\overline{X_c})$ are the mean values of a given variable in the treatment and the control group, respectively. The natural log was used for meta-analyses because its bias is small and its sampling distribution is approximately normal (Luo et al., 2006). The variance (ν) of RR was estimated as:

$$\nu = \frac{S_t^2}{n_t\overline{X_t^2}} + \frac{S_c^2}{n_c\overline{X_c^2}} \tag{2}$$

where n_t and n_c are the sample sizes for the treatment and control groups, respectively; and s_t and s_c are the standard deviations for the treatment and control groups, respectively.

To test whether the experimental conditions alter the response magnitude to N addition, each observation was categorized into three groups: ecosystem type, N addition rate, and forms of N addition. The data were sub-divided and the mean of response ratio (RR_{++}) and standard error [$s(\mathrm{RR}_{++})$] were calculated as:

$$\mathrm{RR}_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k_i} W_{ij}\mathrm{RR}_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k_i} W_{ij}} \tag{3}$$

$$s(\mathrm{RR}_{++}) = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k_i} W_{ij}}} \tag{4}$$

where *m* is the number of groups (e.g., different N addition levels, N forms or ecosystem types), k_i is the number of comparisons in the *i*th group, and W_{ij} is the weighting factor and was estimated as: