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Research paper

Sequestration of atmospheric CO_2 in boreal forest carbon pools in northeastern China: Effects of nitrogen deposition

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ABSTRACT

An increase in nitrogen (N) deposition has been proposed to cause boreal forests to capture and store a globally significant quantity of carbon (C), but the size of the boreal forest C sink remains uncertain after N addition. Therefore, we conducted a N addition experiment using four N addition rates (0, 2.5, 5.0 and 7.5 g N m^{-2} yr^{-1}) in the boreal zone of northeastern China to determine the changes in forest C sequestration and to investigate the mechanisms of the changes in C sequestration after N addition. Our data show that N addition increases the total C sequestration, but the efficiency of this effect is reduced as the N addition rate increases. We also found that the amount and the mechanism of the C sequestration increase in above- and belowground C pools vary with different amounts of N addition. Low- and medium-N addition increased the above- and belowground C sequestration, and the potential mechanisms responsible for such C accumulation include N-induced increases in photosynthesis via a decrease in the foliar C content and increases in root mass via increased plant C allocation in the roots. However, high-N addition decreases aboveground C sequestration by inhibiting photosynthesis and increases belowground C sequestration by inhibiting soil C losses. Our data indicate that the response patterns of above- and belowground C pools to different amounts of N addition may involve several complex biochemical processes and occur by different mechanisms; therefore, separating the effects of N addition on above- and belowground C sequestration will help improve and validate current modeling efforts.

1. Introduction

The Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC) underscores the high likelihood of significant future global climate warming if greenhouse gas (GHG) emissions continuously increase (IPCC, 2013). Global climate warming is one of the greatest threats to human health and animal and plant survival. Thus, atmospheric CO_2 mitigation has attracted much attention. Several carbon (C) capture and storage schemes have been developed (Von der Assen et al., 2013; Boot-Handford et al., 2014). However, biological CO_2 disposal (e.g., the absorption of CO_2 by plant photosynthesis) is more beneficial for reducing side effects compared to chemical and engineering techniques – such gas treatment techniques intrinsically produce CO_2 and consume energy (Boot-Handford et al., 2014). One biological C capture scenario involves sequestering atmospheric CO_2 in terrestrial ecosystem C pools, including plant C pools and soil C storage with secure storage and long residence times, to mitigate global warming. Pan et al. (2011) suggested that a third of annual CO_2 emissions is captured and stored by terrestrial ecosystems, and Birdsey et al. (2006) also showed that forests in the U.S. form a C sink that sequesters approximately 10% of the annual U.S. CO_2 emissions. However, the sequestration of atmospheric CO_2 in terrestrial ecosystems predominantly occurs in forest ecosystems, so forests play a key role in mitigating climate change.

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Boreal forests are an important forest ecosystem that covers approximately 15% of the land surface area and have been identified as significant sinks for atmospheric CO_2 (Francet et al., 1995; Malhi et al., 1999). Large amounts of C are captured and accumulated in plants, and soil organic matter in boreal forests may serve to partly offset GHG emissions, thus significantly mitigating CO_2-induced climate change. Nevertheless, nitrogen (N) is often the most limiting nutrient for plant growth and C sequestration in boreal forest ecosystems, and limited N availability in nature reduces the C storage potential of boreal forests (Vitousek and Howarth, 1991; Kimmins et al., 2010; Wieder et al., 2015). Wieder et al. (2015) suggested that C capture and storage can be heavily limited by low soil N availability in boreal forests. Therefore, C capture and storage in boreal forests can be enhanced through N deposition due to low levels of N availability in the soil (Schimel et al., 2001; Jacobson and Pettersson, 2010; Maaroufi et al., 2015). Previous studies on forest C pools along gradients of N deposition have shown that some trees exhibit increased C capture and storage in response to higher N deposition (Jacobson and Pettersson, 2010; Maaroufi et al., 2015), while others do not (Thomas et al., 2010). These results indicate that the addition of small amounts of N can benefit N-limited ecosystems, as N deposition can increase terrestrial C sequestration and thus decrease the rate of CO_2 accumulation in the atmosphere. The potentially detrimental effects of excessive N deposition, such as soil acidification, higher levels of toxic aluminum (Al^{3+}) and depletion of base cations, have also been emphasized in reference to non-N-limited and N-saturated systems formed through chronic N deposition (Wallace et al., 2007). The quantitative effects of N deposition on forest growth and C sequestration are arguable (Liu and Greaver, 2009; Dezi et al., 2010; Zaehle et al., 2011). However, increased N deposition may alleviate N limitation (Gruber and Galloway, 2008) and alter boreal forest C pools (Högberg et al., 2006). N deposition may regulate the rate at which biological mechanisms capture CO_2 in boreal forests. Large fractions of terrestrial C are found in boreal forests, so it is important to consider probable boreal forest C pool responses to N deposition.

Therefore, an accurate prediction of the responses of the above- and belowground C storage in boreal forests to N deposition is critical for developing climate change targets and formulating government policies. Increasing atmospheric N deposition may affect the aboveground C pools in boreal forests by changing plant photosynthesis processes. Due to limited N in boreal forests, N deposition may stimulate the foliar biomass and photosynthetic efficiency, increasing C capture from the atmosphere and C sequestration in the plant biomass (Thomas et al., 2010; Fleischer et al., 2013; Gundale et al., 2014). Thomas et al. (2010) suggested that N deposition increases the aboveground biomass by 61 kg C per kg N deposited, while Gundale et al. (2014) showed that a small quantity of annual anthropogenic CO_2 emissions is sequestered in boreal forests as a result of N deposition. In addition, chronic N deposition can lead to N saturation or supersaturation in boreal forest soil, and this may slow plant growth (Elias et al., 2009). However, uncertainties remain regarding the magnitude by which N deposition enhances or inhibits C sequestration in the aboveground biomass in boreal forests.

In addition to the aboveground C pools, forest soils retain a larger and more persistent C pool than that contained aboveground, representing a potentially important reservoir for enhanced terrestrial ecosystem C storage in response to N deposition (Pregitzer and Euskirchen, 2008; Lovett et al., 2013). Some studies that evaluated the impact of N deposition on soil sequestration have shown that N deposition may enhance the belowground C pools in boreal forest soils (Högberg et al., 2006; Maaroufi et al., 2015). Several underlying mechanisms have been proposed to determine the enhancement of soil C pools by N deposition: (1) the suppression of organic matter decomposition via the inhibition of decomposition enzyme activities (Janssens et al., 2010; Ramirez et al., 2012; Cusack, 2013) (2) the suppression of heterotrophic respiration and changes in the microbial community (Janssens et al., 2010; Ramirez et al., 2012; Cusack, 2013; Frey et al., 2014) and (3) increased soil C input from litterfall and roots (Lu et al., 2011). However, Du et al. (2014) showed that an increased CO_2 efflux due to N deposition causes the soil C pool to decrease, while the opposite is the case when soil C pools increase. Thus, soil C pool responses to N deposition may be nonlinear and may fluctuate. Soil C pools form larger forest C pools (Goodale and Davidson, 2002), and improving our understanding of N-induced soil C storage is critical to accurately predict how boreal forest responses to increased N deposition may greatly affect the soil C sequestration capacity.

Most research on N deposition is focused on boreal and temperate regions in which N is generally limited (Thomas et al., 2010). However, the size of the boreal forest sink under N deposition remains uncertain. A better estimate of the future changes in the connections between boreal forest C pools and environmental N deposition is also required. The objective of this study is to assess the effects of N deposition on C sequestration in a boreal forest ecosystem. The net impact of N deposition on C sequestration in boreal forests is not only a scientific issue but also may have political ramifications by influencing N deposition for C emission reduction strategy development. In addition, understanding the mechanisms by which C storage in forest soils may be affected by increasing rates of N deposition is important for understanding ecosystem functions under conditions of global climate change. We hypothesized that N deposition should (1) increase C storage in trees by increasing photosynthesis and (2) decrease soil C emission by reducing the soil respiration rate. We performed experiments in which different amounts of N were added to investigate C sequestration patterns in boreal forests and some potential mechanisms that might affect them.

2. Materials and methods

2.1. Study sites and sampling overview

Our N addition experiment was conducted in a boreal coniferous forest located in the Nanwenghe National Natural Reserve (51°05′–51°39′N, 125°07′–125°50′E) in the Greater Khingan Mountains of northeastern China. The study area is characterized by a cold temperate continental climate with a long, cold winter (October–April) and a short, warm summer (May–September). The mean annual temperature is −2.4 °C. The monthly mean temperature ranges from −26.3 °C in January to 18.6 °C in July. The mean annual precipitation is 489.2 mm, and most of the rainfall occurs in July and August. The soil is classified as a sandy soil (includes many stones) based on an international soil classification system (http://www.iuss.org/index.php?article_id=175), and the mean soil thickness is 20 cm. The predominant tree species is *Larix gmelinii,* which has a mean stand density of 2852 ± 99 trees hm^{-2} and a mean diameter at breast height (1.3 m height, DBH) of 8.98 ± 0.32 cm.

2.2. Experimental design

We performed one N addition experiment under stand conditions typical of those of the study site. Three blocks were randomly created in 2011, and each block included four 20 m × 20 m plots. Each plot was separated by a 10 m wide buffer strip. We employed a method widely used in previous studies (double and triple the local N deposition rate) to simulate N deposition (Song et al., 2016) and assumed a northern N deposition rate of 2.5 g N m^{-2} yr^{-1} in China (Liu et al., 2013). Thus, we treated each block with four N levels: a control (no added N), low-N (2.5 g N m^{-2} yr^{-1}), medium-N (5 g N m^{-2} yr^{-1}) and high-N (7.5 g N m^{-2} yr^{-1}). The four N treatments were randomly assigned across the four plots, with three replicates of each treatment. N was added as ammonium nitrate (NH_4NO_3) from May of 2011 and was distributed on five occasions during each growing season (from May to September). For each N application, NH_4NO_3 was weighed, dissolved in 32 L of distilled water and then applied with a backpack sprayer below