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Effects of nitrogen deposition on carbon sequestration in Chinese fir forest ecosystems

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ABSTRACT

Nitrogen deposition and its ecological effects on forest ecosystems have received global attention.
We used the ecosystem model FORECAST to assess the effects of nitrogen deposition on carbon sequestration in Chinese fir planted forests in SE China. This topic is important as China is intensifying its reforestation efforts to increase forest carbon sequestration for combating climate change impacts, using Chinese fir as the most important plantation species. A series of scenarios including seven N deposition levels (1, 5, 10, 20, 30, 40 and 50 kg ha^{-1} y^{-1}), three management regime (rotation lengths of 15, 30 and 50 years) and two site qualities (nutrient poor and fertile sites) were defined for the simulations. Our results showed that N deposition increased carbon sequestration in Chinese fir forests, but the efficiency of the increasing effect is reduced as N deposition levels increase. When N deposition levels exceeded 20–30 kg ha^{-1} y^{-1}, the incremental effects of N deposition on forest C pools were marginal. This suggests that N deposition levels above 20–30 kg ha^{-1} y^{-1} could lead to N saturation in Chinese fir forest soils. Any additional amounts of N input from deposition would likely be leached out. Total above-ground C was more sensitive to N deposition than to rotation length and site quality. It was also estimated that the contributions of N deposition to C sequestration in all Chinese fir forests in South-East China are 7.4×10^6 Mg C y^{-1} under the current N deposition levels (5 to 10 kg ha^{-1} y^{-1}) and could reach up to 16×10^6 Mg C y^{-1} if N deposition continues increasing and reaches levels of 7.5 to 15 kg N ha^{-1} y^{-1}.

1. Introduction

Nitrogen is often the most limiting nutrient for tree growth and carbon sequestration (Kimmins et al., 2010). There is a growing research interest in the effects of N deposition on carbon sequestration in forest ecosystems (Fan and Hong, 2001; Liu et al., 2011; Magnani et al., 2007; Thomas et al., 2010). Increased N input through deposition can affect forest ecosystems in different ways. On one hand, N deposition can increase foliar biomass and photosynthetic efficiency, and thus increase forest ecosystem biomass. On the other hand, N deposition can reduce allocation to fine roots (Litton et al., 2007), reduce respiration rates (Janssens et al., 2010), accelerate N saturation in areas of high nitrogen in soils, and consequently cause leaching loss of N and other nutrients (e.g. base cations) to aquatic systems (Kimmins et al., 2010). Aber et al. (1998) suggested that net primary production (NPP) may at first increase with increasing N deposition, but then decline with N saturation. Although NPP does not account for respiration and organic matter decomposition, NPP is the main process to acquire atmospheric C and therefore an increase in sequestered C with increasing NPP as a result of enhanced N deposition rates could be expected. This hypothesis has latter been corroborated. For example, Magnani et al. (2007) found that N deposition plays a critical positive role in forest C sequestration in boreal and temperate forests. Based on forest inventory data, Thomas et al. (2010) showed that the N deposition with a range of 3 to 11 kg ha^{-1} y^{-1} increased above-ground biomass by 61 kg C per kg N deposited. However, other researchers have shown that increased N inputs through deposition only added marginal or no effects to C sequestration (Nadelhoffer et al., 1999; De Vries et al.,

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2008). These conflicting results suggest that the effects of N deposition on C sequestration may be regional or site specific.

Most research on N deposition focuses on boreal and temperate regions where N is generally limited, with much less focus on tropical and sub-tropical regions (De Vries et al., 2008; Hall and Matson, 1999; Thomas et al., 2010). In some of the temperature forest of central Europe, N deposition has already removed N limitation. In addition, different tree species may have different responses to N deposition even in the same region (Thomas et al., 2010). These facts highlight that more research is needed on the various major forest species in tropical and sub-tropical regions. Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) is the most important commercial forest species in subtropical China. It has been widely planted in the southeast provinces of China, being distributed in 14 provinces, with the central area located in Zhejiang, Jiangxi, Hunan and Fujian provinces (Bi et al., 2007; Lu et al., 2002).

Traditionally, Chinese fir plantations were established after native evergreen broad-leaved forests were harvested and slash-burned. The plantation sites were generally abandoned after one or two rotations and allowed to regenerate naturally to mixed species stands by stump sprouting and natural seeding, which then acted as a fallow period to restore the site (Yu, 1997). However, since the 1950s, the plantation area of Chinese fir has been enlarged, and this species has been repeatedly planted on the same sites without intercropping or periods of fallow. Foresters have generally used a 25-year rotation, with variation from 20 to 30 years depending on site quality (i.e., nutrient abundance, Wu, 1984). In the latest years a trend towards shortening the rotation length is being observed, driven by the increasing demand for timber caused by economic development and population increase. Continuous cultivation of Chinese fir at the same site has resulted in a well known ecological problem: yield decline over consecutive rotations (Sheng and Xue, 1992; Yu, 1988). Among various possible reasons, N limitation is the most important factor responsible for yield decline (Li et al., 1993). Nitrogen limitation is the result of N losses during and following timber harvest, post-harvest slash burning and soil erosion in the Chinese fir forests (Bi et al., 2007).

Rapid industrial development has caused the sub-tropical region of China to become one of the major N deposition areas in the world (Richter et al., 2005). The impacts of N deposition on forest C sequestration capacity in Chinese fir plantation forests in sub-tropical China are poorly understood. Several models have been used to assess these impacts. At global scale, Jain et al. (2009) showed the historical enhancement of C sinks by N dynamics with the ISAM model, which could be especially intense in secondary forests (Yang et al., 2010). Townsend et al. (1996) used a perturbation biogeochemistry model (NDEP) and estimated terrestrial C storage increase arising from N deposition. Similar results were reported by Zaehle et al. (2010) using the O–CN model. Regionally, Ollinger et al. (2002) used the model PnET–CN and found that N deposition could have significantly increased tree growth in NE USA. Churkina et al. (2007), using BIOME-BGC, showed that N deposition could significantly increase sequestered C but only in secondary forests. Applying the G'DAY model Dezi et al. (2010) estimated that the C storage capacity of a generic European forest ecosystem was at most 121 kg C kg^{-1} N deposited. In China, Tian et al. (2011) estimated increases in C sequestration under regional variations of N deposition by using the DLEM and TEM models. Zhao et al. (2010) used the GEMS model to estimate increases in C pools along the Yangtze River. Wang et al. (2007) also detected the increase in C sink strength in the latest decades using the InTEC model, an estimation also described by Fang et al. (2001).

The models in these regional to global studies, however, did not simulate individual species but broad functional groups (i.e. deciduous, conifers, etc); and they did not explicitly simulate forest management, except in a simplified way (see Dezi et al., 2010). Therefore, they were not well suited to study the interactions between N deposition and forest management, which are dependent on local factors such as species composition and fertilizer management. To avoid these issues, an ecosystem-level forest management model is more suitable (Kimmins et al., 2008).

The model FORECAST has been used as a management evaluation tool in many types of world forest ecosystems (Bi et al., 2007; Blanco et al., 2007; Blanco and González, 2010a, 2010b; Morris et al., 1997; Sachs and Sollins, 1986; Seely et al.;, 2010; Wang et al., 1995; Wei et al.;, 2000). The model is specially designed to examine the impacts of different management strategies or natural disturbance regimes on long-term site productivity and C sequestration. A detailed description of the FORECAST model can be found in Kimmins et al. (1999, 2010) and a brief description of the algorithms simulating C sequestration and N limitation will be presented in the next section.

The objective of this paper was to evaluate the effects of various levels of N deposition on C sequestration capacity in Chinese fir planted forests. This evaluation was conducted in conjunction with various forest management scenarios (e.g., rotation length, site quality). Our ultimate goal was to understand the potential of a major sub-tropical plantation species for storing C with various levels of N deposition using Chinese fir forests as a study case. The reason for choosing Chinese fir forests are: 1) N-limitation is a common problem in secondary forests of the sub-tropical region, usually as a result of unsustainable forest practices in the past, causing long-term yield decline (Davidson, 2007; LeBauer and Treseder, 2008; Li et al., 1993); 2) Chinese fir forests are perhaps the most studied forest in the sub-tropics, suggesting sufficient data exist for calibrating the FORECAST model; and 3) there are large spatial variations in N deposition in Chinese fir forests resulting from various levels of industrial development in southern China (Fig. 1). All these reasons indicate an excellent opportunity to use Chinese fir as a case study to assess the response of forest ecosystems to N deposition in subtropical forests.

2. Materials and methods

2.1. Chinese fir forest ecosystems

The natural range of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), a typical subtropical coniferous tree species, is in the humid subtropical area in southeast China (Wu, 1984; Yu, 1997), a region of approximately 22 to 34° N and 102 to 123° E (Fig. 1). This is a region of low mountains and hills, with very broken topography and complicated geology. The natural distribution of Chinese fir is as a component of mixed subtropical evergreen broad-leaved forests. Plantations are generally located on slopes of more than 20% because the gentler lower slopes are generally used for agriculture (Bi et al., 2007). Soil type is usually clay-rich red-earth, but the soil may be derived from very different parent materials. The soil conditions vary significantly in terms of texture, depth, fertility and other physical and chemical characteristics. Chinese fir is a species of moderate shade tolerance, but it grows best in full sunlight (Wu, 1984; Yu, 1997). The species is moderately nutrient demanding (Zhong and Hsiung, 1993), and in unmanaged forests it normally grows on moist and fertile sites. The response of Chinese fir to forest fertilization varies with stand age. Growing on yellow-red earth soils, the greatest growth response of young Chinese fir is reported to be to P and K fertilization, while growth in mid and late rotation responds mostly to N (Li et al., 1992a, 1992b, 1993).

Chinese fir is one of the most important timber tree species in China, accounting for 60–80% of the total area of timber plantations in southeast China, and for 20–25% of the national commercial timber output (Lu et al., 2002; Sheng, 1992). The timber of Chinese fir is straight and decay-resistant, and has a long history of being an important construction and furniture material in China. It is the most important fast-growing timber tree of the warm regions south of the Chang Jiang Valley (Wu and Raven, 1999). It can reach a level of timber production in monoculture plantations on good sites of 150 m^3 ha^{-1} at age 10 years and 450 m^3 ha^{-1} at final harvest age of 25–30 years (Lu et