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Will more nitrogen enhance carbon storage in young forest stands in central Appalachia?

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ABSTRACT

Many temperate deciduous forests in the Eastern US are secondary, regrowing forests and have experienced decades of elevated inputs of acidic compounds and biologically available nitrogen (N) from the atmosphere. These young forests play an important role in the global carbon (C) cycle as C sinks, and it is possible that acidic deposition will influence the strength and longevity of this sink. We used the Fernow Experimental Forest Long Term Soil Productivity (LTSP) experiment near Parsons, WV to evaluate how 13 years of experimental N additions has affected ecosystem C storage and stand level dynamics in a young temperate deciduous forest. Specifically we examined whether N additions: (1) directly increased aboveground growth of regenerating trees but did so in a way that was independent of the indirect effects of soil acidification; (2) directly (independent of acidification effects) increased forest floor and soil C pools, and decreased the fine root C pool; and (3) lowered stand density and diversity. We also tested whether tree species were differentially affected by either N fertilization or soil acidification.

Thirteen years of ammonium sulfate additions to a regenerating deciduous forest stimulated C storage by 22% – even in a region with historically high levels of atmospheric N deposition. This response was driven primarily by a 27% increase in C storage in aboveground biomass and to a lesser extent by a 35% increase in C stored in the smaller forest floor pool. Despite the dominance of a single tree species (*Prunus pensylvanica*), the overall response may have been tempered by reductions in stand density and was only detectable when the changes in all species were included, rather than when only the changes in the dominant species were examined. Indirect acidification effects were found to increase C accumulation in the forest floor and decrease the number of different tree species.

In the short-term it is likely that N deposition will stimulate forest growth and C storage in young temperate deciduous forests. However, given the differential responses observed for longer-lived tree species versus the positive response for short-lived species, it appears that the long-term effects of N deposition on C storage in temperate deciduous forests may be different than the short-term effects, and may even be negative.

1. Introduction

The residual terrestrial carbon (C) sink is the implied uptake by terrestrial ecosystems of the ~28% (~2.6 Pg C/yr) of anthropogenic carbon dioxide (CO_2) emissions that cannot be accounted for by atmospheric accumulation or oceanic uptake (Houghton et al., 1998; Le Quere et al., 2012; Pan et al., 2011). Currently, we think that a portion of this residual C uptake occurs on land in the northern temperate latitudes (Ciais et al., 1995). Furthermore, forests in these latitudes, such as those in the Appalachian Mountains of Eastern US, may be responsible for a large portion of the sink (Pan et al., 2011; Schimel, 1995).

Several mechanisms have been proposed for the creation and maintenance of a temperate forest C sink. Increased forest growth following logging and abandoning of agricultural land, as well as the maintenance of secondary, regrowing forests by various silvicultural practices have been implicated as primary contributors to the enhanced C uptake (Goodale et al., 2002). Increased tree growth in response to increasing levels of atmospheric CO_2 may also be responsible for a portion of the C sink (Ainsworth and Long, 2005). Similarly, a fertilization effect from the biologically available nitrogen (N) in acidic deposition may have increased growth of N-limited forest trees (Aber and Driscoll, 1997; Thomas et al., 2010).

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Acidic deposition supplies ecosystems with biologically available forms of N at rates that are substantially greater than pre-industrial levels (Galloway et al., 1976, 1987). Despite recent reductions in acid deposition in the Eastern US due to the Clean Air Act, the levels of N in precipitation in this region are still above pre-industrial levels and likely will remain elevated for some time (Baumgardner et al., 2002; Dentener et al., 2006). Additionally, in other temperate forests, especially in Asia, levels of N deposition are likely to continue to rise in the future (Galloway et al., 2004). However, the effect of acidic deposition on the residual terrestrial C sink is more complex than the effects of forest regrowth or CO_2 fertilization because short-term benefits, such as the alleviation of N limitation, could be diminished, or reversed, by longer-term effects such as the depletion of base cations, lower soil pH, and higher levels of toxic aluminum (Al^{3+}) (Aber et al., 1998).

In the last twenty years there has been a great deal of research on the effect of N deposition on forest C storage, and results vary. Modeling studies (Aber and Driscoll, 1997) and N addition experiments (Magill et al., 2004; Pregitzer et al., 2008), as well as more complex analyses combining models and field measurements (Magnani et al., 2007; Ollinger et al., 2008), have provided evidence that N deposition may enhance the terrestrial C sink – some of which occurs in forest soils. However, ^{15}N tracer studies (Nadelhoffer et al., 1999; Templer et al., 2012) have questioned the likelihood of an increase in aboveground C storage due to elevated N inputs. Additionally, some field studies (Boggs et al., 2005; Magill et al., 1996) have shown a neutral or mixed response to N inputs, and some (Elias et al., 2009; May et al., 2005; McNulty et al., 2005) have even shown declines in forest growth due to N saturation with chronic N inputs. This range of results is likely due to the complex and non-linear responses that can develop during chronic acidification and their dependence on forest history and soil characteristics.

The timing of a shift from a positive to a negative response in aboveground tree C storage due to elevated N inputs may vary with forest type, land-use history, and soil properties. In general, it appears that coniferous forests are more sensitive to enhanced N inputs than deciduous forests (Aber et al., 1998; Magill et al., 2004) and older forests are less likely to utilize N inputs than young, fast-growing forests (Fenn et al., 1998; Vitousek and Reiners, 1975). A further complication is the likelihood that once N availability exceeds biological demand (N saturation), different soils will be more, or less, resilient to leaching of calcium (Ca^{2+}) and magnesium (Mg^{2+}), and to soil acidification. Specifically, trees growing in soils derived from predominantly sandstone parent materials will probably be more susceptible to negative effects than trees growing on soils derived from limestone containing parent material.

Numerous temperate deciduous forests of the Eastern US are secondary, regrowing forests and may be vulnerable to the effects of elevated N inputs because they are not only underlain by base-poor, sandstone-derived soils but have also experienced a significant amount of timber harvest which can permanently remove large quantities of nutrient cations (Adams et al., 2000; Federer et al., 1989). Thus, although these young forests should initially be able to retain N due to a positive response in tree growth, once N saturation develops, the negative effects could come relatively quickly and be difficult to reverse.

In addition to the direct positive or negative changes on tree growth induced by chronically elevated N deposition, it is also possible that elevated N deposition could result in long-lived alterations in forest C sequestration by changing stand dynamics or species composition. Little research has focused on the effect of N inputs on stand-level changes in regenerating forests where differential species responses to nutrient level changes could alter competitive relationships and community structure in later successional stages (Adams, 2003). However, work in old fields (Stevens and Carson, 1999), and in grasslands and heathlands (Tilman, 1993; Vitousek et al., 1997) demonstrated that elevated N inputs can significantly change community level variables and lead to lower diversity. Research in temperate deciduous forests using a N deposition gradient (Boggs et al., 2005), forest inventory data (Thomas et al., 2010), and watershed fertilization (DeWalle et al., 2006; May et al., 2005) has shown that different tree species respond differently to elevated N. Also, more fertile sites have accelerated self-thinning resulting in fewer, larger trees than less fertile sites (Stevens and Carson, 1999). It therefore seems likely that, given enough time, acidic deposition will change stand dynamics and/or tree species composition in temperate deciduous forests in ways that could alter their capacity to sequester atmospheric C.

Although aboveground growth in temperate deciduous forests is often considered to be responsive to N additions, increasing N inputs can also alter belowground processes. For example, it has been observed that increased N availability in forests is associated with reduced fine root biomass and the amount of C stored in this pool (Jia et al., 2010; Nadelhoffer, 2000; Nadelhoffer et al., 1985). N inputs may also affect the composition of the soil microbial community and the expression of extracellular enzymes in ways that enhance C storage in the litter layer (DeForest et al., 2005; Fog, 1988; Knorr et al., 2005; Zak et al., 2008) and soil (Ramirez et al., 2012; Whittinghill et al., 2012) of forests. Thus, the response of the temperate deciduous forest C sink to N deposition will be the sum of both the above- and belowground pool responses.

The Fernow Experimental Forest Long Term Soil Productivity Experiment (LTSP) near Parsons, WV (Adams et al., 2004) provides a unique opportunity to evaluate how experimental N additions, and the associated soil acidification, have affected ecosystem C storage and stand level dynamics in a temperate deciduous forest during the first 13 years of forest regeneration. Using this experiment, we were able to test several hypotheses based on our current understanding of how N additions alter the ability of forests to sequester C. Specifically, we examined whether N additions: (1) directly increased aboveground growth of regenerating trees but did so in a way that was independent of the indirect effects of acidification (e.g., loss of nutrient cations, lower soil pH, and/or elevated Al^{3+}); (2) directly (independent of acidification effects) enhanced forest floor and soil C pools, and lowered the fine root C pool; and (3) lowered stand density and diversity. We also examined whether tree species were differentially affected by either N fertilization or soil acidification.

2. Materials and methods

This study was done in the Fernow Experimental Forest LTSP plots near Parsons, WV (39°04′N, 79°41′W) (Adams et al., 2004). The location of the Fernow LTSP experiment has a SE aspect, and slopes between 15% and 31%. It is situated in the Allegheny Mountain subsection of the Appalachian Physiographic Province and has an elevation range of 798–847 m. Soils are classified as loamy-skeletal, mixed active, mesic typic Dystrudepts and the parent materials are sandstone colluvium, sandstone residuum, and weathered shale. Prior to the initiation of the experiment in 1996, the most recent logging activity occurred in ~1910, and most trees were ~85 years old. The forest community before the experiment started was classified as a central Appalachian mixed hardwood forest. *Acer saccharum*, *Quercus rubra*, *Acer pensylvanicum*, and *Prunus serotina* together accounted for 2/3 of the total importance value in this forest, and there were 584 stems/ha (0.06 stems/m^2) and 312 metric ton/ha (31.2 kg/m^2) of aboveground tree biomass. There was 1.5 kg/m^2 of forest floor, and the average C content of the forest floor was 45%. The top 15 cm of