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The effects of urea fertilization on carbon sequestration in Douglas-fir plantations of the coastal Pacific Northwest

Benjamin Shryock [a,*], Kim Littke [a], Marcia Ciol [b], David Briggs [a], Robert Harrison [a]

[a] School of Environmental and Forest Science, University of Washington, Seattle, WA 98195, United States
[b] Department of Physical Medicine and Rehabilitation, University of Washington, Seattle, WA 98195, United States

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ABSTRACT

If long-term carbon (C) sequestration can be quantifiably attributed to forest plantation nitrogen (N) fertilization, the net C credits could be used to offset the rising cost of fertilization and C released during the production, transportation, and application of N fertilizer and the effect of NO_x volatilized after application. The purpose of our study was to determine the net change in C sequestration following N fertilization of second-growth Douglas-fir (*Psuedotsuga menziesii* [Mirb.] Franco) plantations in the Pacific Northwest. The C content of the trees, understory vegetation, forest floor, and mineral soil was quantified at age 26–33 at five sites, each with a fertilized plot that received a total of 896–1120 kg N ha^{-1} as urea over 16 years paired with an unfertilized control plot. Tree biomass was estimated using biometric equations and by subtracting the difference between treatment and control at the year of site establishment from the difference between treatment and control final measurement. Understory vegetation on the fertilized plots contained significantly more C than on the control plots (0.2 Mg C ha^{-1}, S.D. 0.2). Nitrogen fertilization significantly increased C sequestered per tree by 2.2 Mg C ha^{-1} (S.D. 1.8), but there was no significant increase in C sequestered in trees per plot. No significant change was found in forest floor, A horizon, and subsoil C contents due to fertilization. These results indicate that, while there is a greater amount of C stored per tree after fertilization, there was more difficulty in accessing C sequestration in forest plantations due to tree mortality and assumed soil variability between plots.

1. Introduction

Since the early 1750s, humans have had a profound effect on the global carbon cycle. Though efforts have begun to reduce this effect, volatilization rates are still well above fixation rates (NRC, 2010). The increasing level of atmospheric carbon dioxide (CO_2), a greenhouse gas, is considered the primary human factor associated with global climate change, most visibly through increasing atmospheric CO_2 concentration from the combustion of fossil fuels, deforestation, and conversion of wildlands to areas of human use (Vitousek, 1994).

Numerous government policies, such as taxes or credits that create an economic incentive for individuals and corporations to reduce atmospheric CO_2 concentration, have been debated as mechanisms to mitigate the effects of global climate change (Bird et al., 2008; Lippke and Perez-Garcia, 2008; Stavins, 2008). Potentially, any human effort that could result in mitigation of CO_2, either by reducing emissions or by removing it from the atmosphere, would have a salable financial value under these programs.

Increasing the productivity of forest plantations, which can often be achieved by nitrogen fertilization, may accelerate carbon sequestration (Barclay and Brix, 1985; Johnson and Kern, 1990; Smith et al., 1993; Adams et al., 2005; Magnani et al., 2007). This is particularly applicable to stands of Douglas-fir (*Psuedotsuga menziesii* [Mirb.] Franco; Fenn et al., 1998; Fisher and Binkley, 2000; Chapin et al., 2002) in temperate ecosystems, which can contain a large amount of biomass (Ares et al., 2007) and are typically N limited (Vitousek and Howarth, 1991). The effects of N fertilizer have received increased attention because C sequestration resulting from N fertilization could be a source of carbon credits and would be an eligible management practice under Article 3.4 of the Kyoto Protocol (Jassal et al., 2008). However, the net effect of fertilization on C sequestration would require accounting for carbon (C) released during the production, transportation, and application of nitrogen (N) fertilizer. Although C emissions from forest emissions will vary by distance from the source of fertilizer, method of application and type of fertilizer applied, a detailed

* Corresponding author. Address: University of Washington, School of Environmental and Forest Science, Box 352100, Seattle, WA 98195-2100, United States. Tel.: +1 775 843 4412.

E-mail addresses: bshryock@u.washington.edu (B. Shryock), littkek@u.washington.edu (K. Littke), marciac@u.washington.edu (M. Ciol), dbriggs@u.washington.edu (D. Briggs), robh@u.washington.edu (R. Harrison).

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analysis of southeastern pine plantations by Markewitz (2006) determined there is a net increase C sequestered following fertilization if the silviculture products are long-lived, such as lumber. However, pulp and paper production would lead to a net decrease. The amount of fertilizer volatilized as NO_x, which has been estimated at 0.55% of total N applied (Stehfest and Bouwman, 2006) must also be considered. It is important that any mitigation effects be well documented scientifically on a case by case basis if policy-created financial incentives are to be justified.

Knowledge regarding the changes in carbon pools of all ecosystem components and site types is vital for a complete understanding of how N additions affect C sequestration. Several studies have examined the effects of nitrogen fertilization on carbon sequestration. However, the results were not consistent (Jandl et al., 2007; Hobbie, 2008). Although the trees often grow more quickly after fertilization (Van Cleve and Moore, 1978), the rates of mineralization and respiration in the soil may increase as the soil carbon to nitrogen (C:N) ratio decreases (Harrison et al., 1996; Hobbie, 2005). Increased soil C mineralization, coupled with physiological changes in the tree tissue, may result in a temporary decrease in overall C sequestration, particularly when fertilizer is repeatedly applied. The impacts of N fertilization on the soil are just as important as the effects on the overstory because the soil is a large and relatively stable pool of carbon in the environment, by some estimates accounting for nearly 80% of terrestrial C (Harrison et al., 1994). Thus, small changes in soil C can result in much larger effects on global C than equivalent changes in terrestrial vegetation, particularly if the harvested trees are not used in long-term product applications.

A meta-analysis by Johnson and Curtis (2001) indicated that synthetic N fertilizers increased surface soil C contents by nearly 40% and whole soil C contents by approximately 20%. Similarly, Leggett and Kelting (2006) reported increased C sequestration in the soil and in the above- and belowground tissue of loblolly pines after N fertilization. Olsson et al. (2005) detected a large increase in aboveground C sequestration after fertilization of Norway spruce, which was partially attributed to a redistribution of C away from the roots. Additional studies have found an overall increase of C sequestration after fertilization (Baker et al., 1986; Nohrstedt et al., 1989). In contrast, other studies have found no significant changes in soil C after planting N-fixing plant species (Paschke et al., 1989) or after applying N fertilizer (Harding and Jokela, 1994; Canary et al., 2000; Adams et al., 2005). Furthermore, a meta-analysis by Knorr et al. (2005) indicated that there was no significant effect of N fertilization on decomposition.

To date there is insufficient evidence to create a prediction model of the ecosystem-wide effects of urea fertilization on Douglas-fir plantations because few studies also examine the C content of the understory, forest floor, and soils of paired control and treatment plots (Adams et al., 2005; Canary et al., 2000). One possible reason for this lack of data is that the necessary large-scale or long-term studies can be costly and time-consuming.

This study aimed to: (1) quantify C sequestered in 26–33 year-old control and urea-fertilized Douglas-fir plantations, and (2) compare the control plots to the fertilized plots to determine the impact of urea-fertilization on C sequestration in live trees, understory vegetation, forest floor, and mineral soil. These results will contribute to the growing pool of knowledge regarding the long-term effects of forest fertilization.

2. Materials and methods

2.1. Site description and location

From 1987 to 1992 five sites were established on forest plantations in western Washington and Oregon (Maguire et al., 1991) in the Tsuga heterophylla zone (Franklin and Dyrness, 1973) (Fig. 1). The sites ranged from 168 to 671 meter elevation and 0–40% average slope. Precipitation was lowest at the Sandy Shore site (751 mm $year^{-1}$) and highest at the Roaring River site (1778 mm $year^{-1}$). The oldest plantation used in this study was planted in 1976, while the youngest was planted in 1984 (see Fig. 2, Table 1).

In each site, two square measurement plots of 0.2 ha with a 9.3 m buffer zone on each side, were selected. Treatment and control plots were thinned from an average of 1149 initial stems per hectare (ISPH) to one quarter the initial density when the plots were installed (~10 years after planting). The plots that were thinned to one quarter of the ISPH were selected for this study because they most closely resemble the stocking rate of regional Douglas-fir plantations at harvest (Brix and Mitchell, 1983).

One plot at each site was randomly selected to be fertilized with 224 kg N as urea per hectare upon site establishment and, subsequently, every 4 years for 16 years. Five fertilizer applications resulted in a total application of 1,120 kg N ha^{-1} as urea on the treatment plots of 4 of the sites, while one site (Twin Peaks) was fertilized four times for a total application of 896 kg N ha^{-1} (Table 1). The control plots were not fertilized. While 1120 kg N ha^{-1} is a high level of fertilization, the treatment rate of 224 kg N ha^{-1} used in this study is the standard operational rate. Also, many plantations are treated with fertilizer multiple times before harvest because the growth effects of previous fertilization tend to decrease after 8 years (Peterson and Gessel, 1983).

2.2. Tree carbon

The diameter at breast height (DBH) (measured at 1.3 m) of each tree was measured at the time of plot installation and every 4 years thereafter, coinciding with the 4–5 fertilizer applications. Live tree diameters were taken during plot installation and during the last measurement period closest to 2009, which was 2007 for Ostrander Road (total age 33), 2008 for Twin Peaks (total age 26), 2009 for Roaring River (total age 32), 2009 for Silver Creek (total age 29), and 2006 for Sandy Shore (total age 27).

Using the equations developed by Gholz et al. (1979), the biomass for each living tree in the plot was calculated for the start and the end of the study. The tree biomass was multiplied by 0.509, which represents Mg C per Mg of $biomass^{-1}$ (Canary et al., 2000; Adams et al., 2005), yielding an estimate of the C sequestered per tree. Tree C was then summed by plot and measurement. For each plot, the total starting tree C was subtracted from the total ending tree C and then divided by the number of trees per plot and the number of years from the start to the end of the study to determine the amount of C sequestered per tree per year on each plot. The change in total C per plot was also measured by subtracting starting total C from ending total C and expanding the data from plot size to per hectare to estimate the C sequestered per hectare. Possible changes in relative allocation of C to different tree tissue were not accounted for and the amount of carbon sequestered in snags was not accounted for.

2.3. Understory carbon

In late fall and winter at five random locations in each plot, all understory plants were clipped to ground level within a 0.25 m^2 area and dried at room temperature. The average weight of the five samples was calculated and the conversion factor of 0.509 g C g $biomass^{-1}$ was applied to determine the average weight of carbon per hectare. Field samples of understory vegetation (as well as forest floor and soil) were collected from October 2008 to January 2009.