FERTILIZATION INCREASES BELOW-GROUND CARBON SEQUESTRATION OF LOBLOLLY PINE PLANTATIONS

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Abstract

The extent of fertilization of southern pine forests is increasing rapidly; industrial fertilization increased from 16,200 ha per year in 1988, to 344,250 ha in 1998. Fertilization increases stand productivity and can increase carbon (C) sequestration by: 1) increasing above-ground standing C; 2) increasing C stored in forest products; and 3) increasing below-ground C pools. This talk will concentrate on the latter and will present summary data from five experiments spatially ranging from the Virginia Piedmont to the Alabama Coastal Plain, and ranging in age from one to 17 years. Fertilization has increased pine growth in all of these studies. In two other studies, fertilization has significantly decreased C losses from the soil as measured via an automated CO_2 efflux system using an infrared gas analyzer. In two more of these studies, soil CO_2 efflux did not differ significantly between control and fertilized plots (means under fertilization were lower though), although below-ground biomass was increased. And in the last study, fertilization increased soil CO_2 efflux by approximately 18%; however, fertilization increased below-ground biomass by more than 250%. Combined, these studies indicate forest fertilization increases below-ground C sequestration. As forest industry is firmly established in the Southeastern United States, and since soil nutrition is a major limiting factor to tree growth, increasing forest fertilization represents a realistic method to sequester atmospheric C in the short- to long-term.

Introduction

One potential mechanism for reducing net carbon (C) emissions is through biological sequestration into forests (Birdsey and Heath 1997). Managed southern pine forests have played a large role, steadily increasing in land area over the past half century. The South represents about 24% of the land area of the United States and is the most actively managed forest resource in the world; from 1962 to 1992 the total land area of commercial pine forest rose 27% to 11,291 million ha (27,889 million acres) (Powell et al. 1993). The extent of managed forests has increased because southern pine forests are extremely productive (Schultz 1997). Intensive management of Southern pine plantations, using competition control, fertilization, and superior genotypes, can now increase productivity three-fold (Borders and Bailey 2000).

In managed forests, the amount of C sequestered (relative to a reference date) will be determined by three factors: 1) the increased amount of C in standing biomass (due to land use changes and increased productivity); 2) the amount of recalcitrant C remaining belowground at the end of the rotation; and 3) the amount of C sequestered in products created from the harvested wood, including their final disposition. Therefore, managed southern pine forests sequester C both *in situ* (biomass and soil) and *ex situ* (products); Figure 1 displays a simple model useful for conceptualizing C sequestration in southern forests.

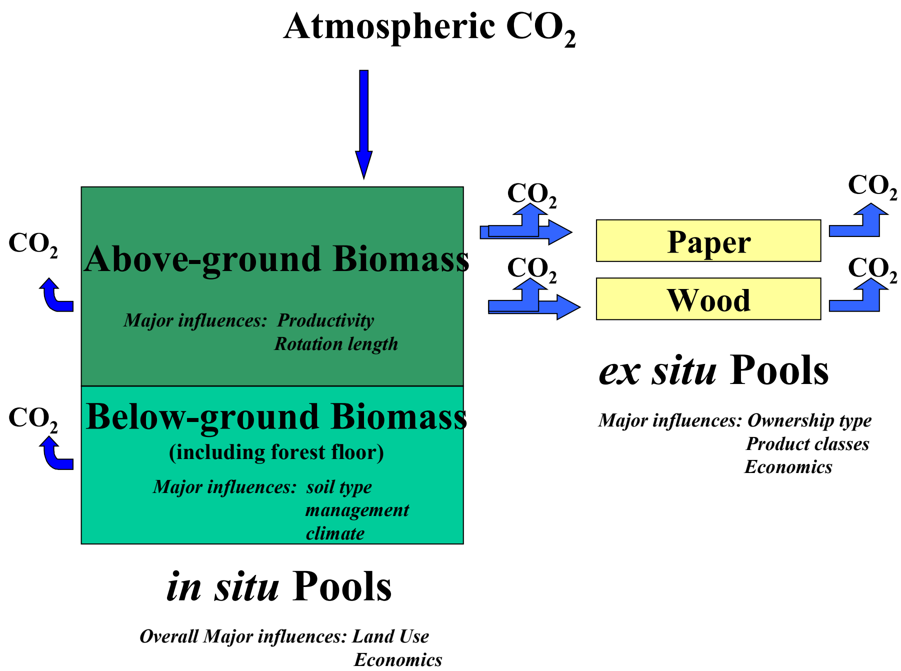

Figure 1. Conceptual model of carbon sequestration of managed forests. ***From:*** **Johnsen et al. 2001. Reprinted with permission of the Society of American Foresters.**

The *in situ* C pool can be increased by increasing stand productivity. Loblolly pine (*Pinus taeda* L.) is a tremendously plastic species that is very responsive to forest management. Operational applications of fertilizer have been shown to consistently increase productivity across a large range in southern pine sites (Schultz 1997). In response, industrial fertilization increased from 16,200 ha (40,000 acres) per year in 1988, to 344,250 ha (850,000 acres) in 1998.

Increased biomass may, in fact, represent a major component of increasing total ecosystem C storage. However, soil is typically the greatest reservoir of C in a forested ecoystem (Schlesinger 1995) and increases in C losses via soil respiration could potentially outweigh C gains via growth increases. In this paper, we explore the impacts of fertilization on *in situ* C sequestration, particularly on its ability to increase below-ground biomass and its influence on soil CO_2 evolution. We present five different case studies that, as a whole indicate the potential of forest fertilization to increase C sequestration in the short- to long-term. These five studies represent a large range in plantation age, geographic location, fertilizer application technique and rate, and climate (Figure 2). Each of the studies is as at different stages of completion.

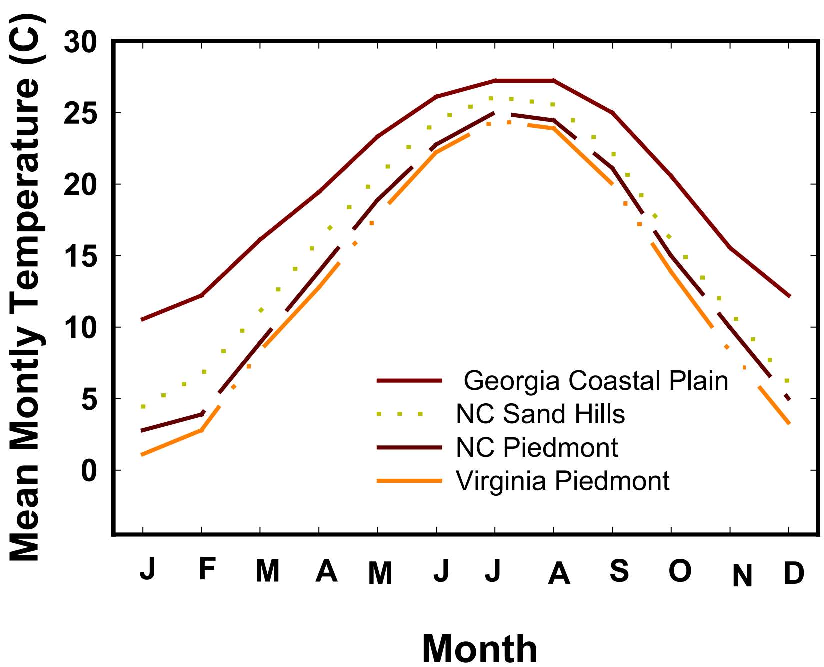

Figure 2. Mean monthly temperatures for the five loblolly pine plantations studied. Note: SETRES and SETRES 2 are both in the NC Sand Hills.

Soil CO_2 Efflux Measurements

Soil, woody debris, root and stem respiration measures are essential to understanding ecosystem C budgets. The Automated CO_2 Efflux System (ACES) is a multi-port, dynamic gas sampling system that utilizes an open flow-through design to measure carbon dioxide fluxes from the forest floor or woody tissue with a variety of chamber styles. It is a composite sampling system that switches sequentially through 16 pressure-equilibrated chambers using solenoid valves. Air is pumped to and from the chamber actively being sampled, flow rates are precisely measured with mass flow meters, and an infrared gas analyzer is used to measure CO_2 efflux from the substrate. Soil and air temperature are measured within each chamber and soil moisture is monitored continuously. Chambers not being sampled are continuously refreshed with reference air. The ACES is fully automated, requiring only periodic calibration checks. ACES (patent pending) was developed by scientists at the USDA Forest Service Southern Research Station in Research Triangle Park, NC and has been used in each of the five following case studies.

Case Studies

One-year-old plantation – Virginia Piedmont

The study was conducted in a loblolly pine plantation located in Buckingham County Virginia (37° 34' N, 78° 26' W) on industrial forestland owned by the Westvaco Corporation. The previous loblolly pine stand was clear-cut in 1995 at age 29 and the current stand was planted in early 1998 after a chop and burn site preparation. Monthly mean temperatures for the site are shown in Figure 2.

The study used a randomized complete block design (15 blocks) with a split-plot, utilizing a factorial combination of 4 treatments. The two treatments considered here are control and fertilization. For fertilized plots a combination of 7.5 g diammonium phosphate and 42 grams ammonium nitrate was applied to achieve a application rate of 115 kg ha^{-1} for nitrogen and 11.5 kg ha^{-1} for phosphorous.

After one year of treatment, fertilized two-year-old seedlings had an above above-ground biomass of 452 g and a below-ground biomass of 232 g, while unfertilized seedling had values of 306 and 162 g, respectively. Soil CO_2 efflux was measured in mid-June, 1999 using the ACES. Although there was a trend for fertilized plots to have lower soil CO_2 efflux rates, there were no statistically significant differences observed between the treatments although there was a trend for rates in fertilized plots to be lower; mean efflux rate was 2.00 and 1.71 μmol CO_2 m^2 s^{-1}. Monthly measures of CO_2 flux using a portable spot measurement system resulted in the same trends (Figure 3). Thus, although seedling below-ground biomass was 43% higher than unfertilized trees, their rates of soil CO_2 efflux were essentially the same. Complete information on this study can be found in Pangle (2000).

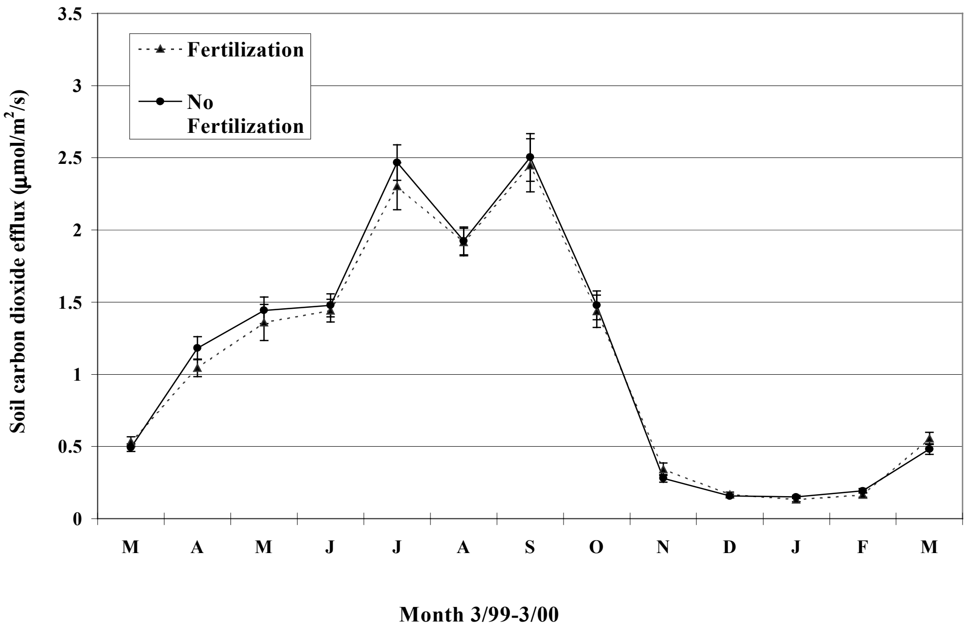

Figure 3. Mean soil CO_2 efflux rates in µmol m^{-2} s^{-1} measured during monthly sampling periods in fertilized and non-fertilized plots in a two-year old loblolly pine plantation located in the Virginia Piedmont. *From*: Pangle (2000)

Six-year-old plantation – Georgia Coastal Plain

The study site is located on the Upper Coastal Plain near Bainbridge, GA (30° 54' N, 84° 35' W) and was established and is maintained by International Paper Company. Monthly mean temperatures for the site are shown in Figure 2. The soils are a sandy loam/san clay loam and was used for soy-bean farming until the year before study establishment. The study has both a hardwood and a pine component, as well as four cultural treatments; only the loblolly pine component under a control and a fertigation treatment are discussed here. Treatment plots were established in January 1995. The control plots received weed control each summer. The fertigation treatment has consisted of weed control and drip irrigation with a fertilizer solution of NH_4NO_3, urea, H_3PO_4 and

K_2O. Full description of the site and treatments can be found in Samuelson (1988) and Samuelson et al. (2001).

Above-ground growth response to fertilization has been dramatic; after four years the control plots had 16.3 Mg ha^{-1} biomass compared to 30.1 Mg ha^{-1} for the fertigated plots. No below-ground biomass is yet available although intensive harvests were conducted in December, 2000 (*note: it is quite obvious the fertigated treatments have much higher root biomass*). ACES was used to measure soil CO_2 flux in September, 2000. Fertigated plots had rates of 2.7 μmol CO_2 m^2 s^{-1} compared to 3.31 μmol CO_2 m^2 s^{-1} for control plots. This trend of lower soil CO_2 efflux of fertigated plots has continued as assessed in monthly spot-measurements (unpublished data).

Six-year-old plantation– North Carolina Sand Hills

The study site is located in Scotland County, North Carolina (35°N lat., 79°W long.) adjacent to the U.S. Forest Service/N.C. State University SETRES (Southeastern Tree Research and Experiment Site) study. Monthly mean temperatures for the site are shown in Figure 2. The soil is sandy, very infertile, and somewhat excessively drained. The site receives an average annual rainfall of 1200 mm. Monthly mean temperatures for the site are shown in Figure 3. Open-pollinated families from the North Carolina and South Carolina Coastal Plain and from the "Lost-Pines" area of Texas were included in the study. Five families from each provenance with average or slightly above average breeding values for volume production were used.

A split-split-plot design was used with the two nutrient treatments as main plots, provenances as sub-plots, and families within provenances as sub-sub-plots The goal has been to supply optimal levels of nutrients each year to stimulate rapid growth. Through the first six growing seasons the total nutrient additions (kg/ha) have been: 425 N, 55 P, 85 K, 3 Ca, 50 Mg, 75 S, 0.5 B, 2 Cu, 5 Fe, 5 Mn, and 2 Zn. More information on the experiment can be found in McKeand et al. 2000.

Trees have been measured for height and diameter each year since planting. In January 1998, 24 trees (12 unfertilized and 12 fertilized were destructively sampled for above-and below-ground biomass (Retzlaff et al. 2001). From September 23 through October 16, 2000 soil CO_2 efflux was measured using ACES on a subset of two blocks.

Fertlization has increased above-ground growth dramatically; at the end of 6^{th} year of growth fertilized plots had over three times the biomass of unfertilized plot both above- and below-ground. In this experiment soil CO_2 efflux was higher in the fertilized (3.59 μmol CO_2 m^2 s^{-1}) than in the control plots (3.05 μmol CO_2 m^2 s^{-1}). However, the almost 300% increase in biomass was associated with only an 18% increase in soil CO_2 efflux.

11-year-old plantation – North Carolina Sand Hills

The study took place at the Southeast Tree Research and Education Site (SETRES), located adjacent to SETRES 2 (described above). The full SETRES study is a 2 × 2 factorial experiment with fertilization and irrigation treatments and four replicate blocks. Fertilization was applied to achieve "optimum" foliar nutrition. For the optimum nutrition treatment, N was applied annually in attempt to achieve a foliar N concentration of 1.3 % with other macro- and micro-nutrients in balance; control foliar N was approximately 0.9%. Fertilization treatment goals have been achieved (Albaugh et al. 1998). More details on the site, stand and treatments can be found in Albaugh et al.(1998).

Of the five case studies, this is the only one where entire stand annual C budget has been estimated. By estimating and summing component processes including net primary productivity, tissue respiration and heterotrophic respiration, Maier and Kress (2000) assessed the impact of fertilization on NEP three years after fertilization commenced. Fertilization greatly increased total NPP and plant respiration, but had little effect on soil CO_2 evolution. Net ecosystem productivity was calculated in a component analysis as the difference in total C used for plant production and total C lost in plant and heterotrophic (soil organisms) respiration. Maier and Kress calculated that non-fertilized stand NEP was slightly negative indicating that at age 11 these stands were still a net source of C to the atmosphere (historically, SETRES was a longleaf pine site on a deep, sandy soil). In contrast, the positive NEP of the fertilized stands indicates these stands were strong C sinks. The large difference in NEP between non-fertilized and fertilized stands was essentially due to increased pine productivity. Soil CO_2 efflux was measured again during the winter of 1999 and although total below-ground biomass of fertilized stands was now 100% greater than non-fertilized stands, soil CO_2 efflux was still the same between the two treatments (1.42 μmol CO_2 m^2 s^{-1}).

17-year-old plantation – North Carolina Piedmont

The work was carried out at Duke Forest (36° N, 70° 56' W) , located in Durham, NC . Monthly mean temperatures for the site are shown in Figure 2. The stands were planted in 1983 with loblolly pine seedlings. In 1998, four pairs of 10 m X 10 m plots, with 20 m minimum buffer between plots were established. In addition, another 30 m diameter circular forest plot was trenched into two halfs to one m deep (deeper than the root zone), an impermeable polyethylene sheet was inserted, and the trench was back-filled. One randomly selected section of the circular plot, and one randomly chosen plot of each newly established plot-pair was fertilized to meet optimal values based on the optimal nutrition management approach similar to that used at SETRES and SETRES 2. Application was 11.2 g N m^{-2} y^{-1} as urea, beginning in July 1998. Each tree within the plot was fitted with a stainless steel dendrometer bands[15] installed at 1.4 m aboveground on all trees in all plots. At the end of the 2000 growing season woody biomass estimates were derived from diameter data using allometric equations. No below-ground biomass assessments have been made. During the entire summer of 2000, ACES was used to measure soil CO_2 efflux in fertilized and non-fertilized plots.

Fertilized plots grew 21% more biomass during the 2000 growth season than non-fertilized plots. This increase is not as dramatic as shown in the other sites. However, the Duke Forest stands are much older than the other stands and fertilizer treatments were not imposed until they were already 15 years old. Fertilizing these older stands decreased soil CO_2 efflux relative to the control; mean rates over the summer were 6.6 and 4.9 μmol CO_2 m^2 s^{-1} in the control and fertilized plots, respectively.

Costs and general productivity benefits of Forest Fertilization

Operational forest fertilization costs \$30 to \$70 per acre. These case studies provided fertilizer at high rates for research purposes, rates higher than used for commercial applications. Southern pine forest growth rates are almost always nutrient limited and forest fertilization in the South is increasing rapidly largely due to the conclusive research conducted by the North Carolina State Forest Nutrition Cooperative; current NCSFNC research indicates growth rates can be increased tremendously by manipulating fertilizer application timing, dose and frequency (NCSFNC 2000). Industrial fertilization increased from 16,200 ha per year in 1988, to 344,250 ha in 1998.

Conclusions

Table 1 provides a summary of responses across the five case studies. In all of the experiments, forest fertilization increased above-ground biomass. The varying responses to fertilizer reflect the great range in stand age, climate and the amount , frequency and timing of fertilizer application. In three of the cases, increases in below-ground biomass were also documented. At the Georgia fertigation study a major belowground harvest has just been completed and it is clear that below-ground biomass increased with fertigation; however, the data is not yet available for analysis. In two of the cases, CO_2 efflux was equal in both fertilized and non-fertilized plot. In two of the other studies, CO_2 efflux was actually lower in fertilized versus non-fertilized plots. In the one case where soil CO_2 efflux did increase (SETRES 2) under fertilization, it did so by only 18% while below-ground biomass was 270% greater.

It appears that forest fertilization can increase C sequestration into perennial root systems of loblolly pine stands. Potentially, such an increase might be totally or partially offset if soil CO_2 efflux increased but these collective studies indicate this will not be the case. Over the course of a plantation rotation, therefore, below-ground biomass provides a short- to medium-term sink for atmospheric C. As rotation ages are compressed the below-ground C pool may further accrue if the root systems decompose at an overall rate shorter than the rotation length. In addition, increased above-ground productivity can provide longer-term C sequestration benefits as biomass is converted to products (Johnsen et al. 2001).

Table 1. Summary of responses to fertilization (% of control mean) for above- and below-ground biomass, and soil CO2 efflux for the five case studies.

Site	Above-ground biomass	Below-ground biomass	Soil CO_2 efflux
VA Piedmont	195%	189%	=
GA Coastal Plain	185%	No data yet	82%
SETRES 2	300%	267%	118%
SETRES 1	200%	200%	=
NC Piedmont	121%	No data yet	75%

The Kyoto protocol stipulates that net C emissions will be decreased below baseline (1990) levels and that verifiable increases in C sequestration might be counted as C credits. Forest fertilization provides an opportunity to increase production of existing forests now under less intensive management, and increase the productivity of future rotations on these same tracts of land. Perhaps even more importantly, it will allow conversion of marginal farmland to highly productive C-sequestering forest plantations.

Research Needs

The data here are presented as five distinct case studies. Currently theses data are being combined in a modeling analysis of soil CO_2 efflux. These analyses will provide a quantitative tool to predict soil C losses as a function of particular environmental conditions. In addition, the studies presented here have been relatively short-term. We still need estimates of the long-term net effects of fertilization on C sequestration. Currently the USDA Forest Service (K. Johnsen) and the University of Georgia (Bob Teskey) are cooperating on a large-scale retrospective study to examine rotation-age stand biomass of all above-and below-ground components using older, established research plots. The goal is to incorporate these new data into an integrated analysis of *in situ* and *ex situ* of C sequestration as described in Johnsen et al. (2001). Such analyses will include the C costs of fertilizer production, transport and application.

Furthermore, N losses from agriculture fields represent a major source of point source pollution to waterways. Forest plantations are fertilized at a lower intensity than agriculture systems. And since they have perennial and extensive root systems that are not disturbed by tilling on a yearly basis, losses of nutrients off the site are much less than in agriculture. However, research, to design fertilizer applications to optimize tree nutrition and minimize losses is imperative for forest fertilization to be conducted in a sustained, environmentally sound manner.

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