EFFECTS OF NUTRIENT AND ORGANIC MATTER MANIPULATION ON CARBON POOLS AND FLUXES IN A YOUNG LOBLOLLY PINE VARIETAL STAND ON THE LOWER COASTAL PLAIN OF SOUTH CAROLINA

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Abstract—Manipulation of site organic matter and nutrients, in addition to planting of superior genotypes will likely influence carbon fluxes from intensively managed forests. The objective of this research is to monitor total soil carbon dioxide (CO_2) efflux (F_S), microbial respiration (R_H), and leaf gas exchange (P_N) in a two-year-old loblolly pine (*Pinus taeda* L.) stand located on the Lower Coastal Plain of South Carolina, which has undergone logging residue (LR) and nutrient additions. Short-term results showed a 17 percent decrease in stem volume with the addition of LR, and showed only modest improvement with the addition of nitrogen (N) and phosphorous (P). However, fertilizer alone increased stem volume by 40 percent and increased P_N in needles produced in 2006. LR and fertilization had no consistent effect on F_S, but showed a tendency to increase and decrease R_H, respectively. Most notably, varieties showed a significant and sustained difference in F_S, which was partially explained by increased R_H and fine-root length. These early results suggest that clonal varieties respond differently to site manipulations and nutrient additions and some of these measured responses have implications for long-term C storage.

INTRODUCTION

Southern pines in the southeastern United States are some of the most intensively managed and highly productive forested ecosystems in the world (Allen and others 2005). Currently, southern pine plantations occupy more than 13 million ha and are forecast to increase 67 percent to 22 million ha by the year 2040 (Wear and Greis 2002). Increasing future demands on forest products produced from these forests as well as growing concern over rising atmospheric CO_2 levels has begged the question, how can we manage these forests to maximize both forest production and carbon sequestration?

A treatment which has long been used in agriculture and mine reclamation is the addition of organic residue to the soil. A tremendous volume of logging residue (LR), up to 5-50 Mg/ha (Allen and others 2006) is generated during a typical harvesting operation of a southern pine stand. This slash represents huge stores of organic carbon, which left exposed to the air will largely oxidize being released back into the atmosphere as carbon dioxide, thereby robbing the site of any potential benefits that may be gained by retaining organic carbon and nutrients. More recently forest managers have begun to spread this logging debris back onto the site in an attempt to keep those nutrients on site. Further, an idea has been proposed to incorporate this LR back to the soil. Not only would this provide nutrients to successive stands, but may additionally increase soil carbon sequestration as it is likely some fraction will remain as recalcitrant soil carbon (C).

Manipulation of site nutrients could lead to large increases in forest productivity as well as help to overcome any immobilization caused by organic additions. Over the last couple decades we have greatly increased our understanding of how to manipulate site nutrients to increase forest productivity. In fact, as of 2005, approximately one half million ha of planted pines have undergone some type of nutrient amendments (Fox and others 2007). As Allen and others (1990, 2005) stated, this is only a fraction of the forested stands that have the potential to respond to fertilization.

As the use of chemical fertilizer increases in intensively managed pine forests it becomes necessary to understand how net ecosystem productivity (NEP) will be impacted by such additions. For instance, it is well established that fertilization will increase above ground productivity due to increased leaf area. Additionally, there is growing evidence that fertilization, specifically nitrogen fertilization, suppresses the rate of decomposition either through reduced microbial activity (Gough and Seiler 2004, Tyree 2005), decreased biomass (Blazier and others 2005, Lee and Jose 2003), changes in microbial populations (Frey and others 2004, Wallenstein and others 2006), or some combination. Either of these outcomes could lead to increased NEP.

Advances in breeding and genetically modified plants to produce superior genotypes have opened an exciting area of research that shows potential for increasing productivity of southern pine forests. Allen and others (2005) estimated volume gains from 10 to 30 percent in superior clones over standard planting stock. Improvements in carbon allocation, photosynthetic capacity, drought and pest tolerance, and resource use efficiency are a few ways in which carbon capture (yield) can be increased.

Changes made to site organic matter and nutrients can have diverse and long lasting impacts on site carbon pools and fluxes, and ultimately, on the carbon balance of a site. NEP is the difference between two competing processes. 1. The capture of inorganic C in the form of CO_2 from the atmosphere and its fixation into biomass (gross primary productivity, GPP) minus growth and maintenance respiration (net primary productivity, NPP). 2. The release of CO_2 back into the atmosphere as a result of decomposition and oxidation of soil organic C by soil microbes (heterotrophic respiration, R_H). Active management of site nutrients and LR may dramatically impact one or both of these processes making our understanding of these changes crucial to our ability to manage, control, and predict changes to NEP on intensively managed pine forests. This research utilizes a two-year-old loblolly pine (*Pinus taeda* L.) varietal plantation

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Citation for proceedings: Stanturf, John A., ed. 2010. Proceedings of the 14th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-121. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 614 p.

located on the Lower Coastal Plain of South Carolina. The objectives are to determine how manipulation of site C and nutrients impact aboveground stem biomass, net photosynthesis, total CO_2 efflux, and microbial respiration between two superior loblolly pine varieties one year after treatment initiation.

MATERIAL AND METHODS

Site Description

The site is located in Berkeley County, SC. Elevation is 24 m above mean sea level. Average yearly temperature is 17.8 °C with average daily maximum of 24.1 °C and an average daily minimum of 11.6 °C. Highest daily average temperature is 26.7 °C which occurs during July, and a low of 8.2 °C, which occurs in January. Average yearly precipitation is 120 cm with the highest rainfall of 18 cm in July and a low of 5 cm occurring in November. The dominant soil series on site is Ocilla (loamy, siliceous, semiactive, thermic Aquic Arenic Paleudults). The previous 21-year-old loblolly pine stand was harvested in May 2004 and sheared in June 2004. Logging residue was spread by hand in June and July 2004. Site preparation (bedding) took place in October 2004, and the current loblolly pine seedlings were planted in January and February of 2005.

Experimental Design

This study is designed as a split-plot randomized complete block design replicated three times with the whole-plot treatments arranged in a full 2 by 2 factorial measured repeatedly. Each 0.18 ha plot was planted with 243 container grown varietal loblolly pine (*Pinus taeda* L.) seedlings in nine rows at 4.3 m between row centers. The logging residue (LR) whole-plot treatment consists of two levels of LR incorporation. No LR incorporated and LR incorporated into the mineral soil at an equivalent rate of 25 Mg/ha ovendry weight (o.d.) concentrated onto the beds. Both LR treatments retained original forest floor of approximately 25 Mg/ha o.d. on the surface. The second whole-plot treatment is two loblolly pine varieties. Variety 93 is considered a high leaf efficiency variety with high stem volume produced per unit leaf area. Variety 32 has a lower leaf efficiency and greater overall leaf area. Each plot is split into two 0.0013 ha measurement plots consisting of six seedlings, which are located at opposite ends of the whole-plot, and serve as the experimental unit (EU). Each EU received one of two fertilizer treatments. No nutrient additions or the addition of 209 kg-N and 116 kg-P/ha in the form of diammonium phosphate and ammonium nitrate. Fertilizer was applied on two separate dates. Roughly 1/3 was applied on April 6, 2006 and the remainder applied on May 8, 2006.

Measurements

Aboveground measurements—Aboveground height and ground-level diameter were measured nine times over the 2006 growing season and used to calculate above ground stem volume (diameter squared x height). Net photosynthesis (P_N) was measured 14 times between January 2006 and 2007 on a single detached fascicle from the upper third, south facing side of the tree between 1100 and 1600 hours. Gas exchange measurements were taken using an open-flow, infrared gas analyzer equipped with a 2 by 3 cm cuvette and a blue-red LED light source (LiCor 6400, Lincoln, Nebraska). Measurements were taken on two seedlings per EU with the following chamber conditions: 1600 µmol/m^2/sec PPFD, 370 µmol/mol reference CO_2 concentration, ambient temperature and humidity, and flow rate at 300 µmol/sec. Following P_N needles were immediately removed and fascicle diameter measured to the nearest 0.01 mm using digital calipers. P_N was expressed per unit leaf area based on the following equation (Ginn and others 1991):

$$LA = (n \times l \times d) + (\pi \times d \times l) \tag{1}$$

where *l* is the length of the needle in the chamber (3 cm), *d* is the diameter of the fascicle measured just above the sheath, and *n* the number of needles in the fascicle.

Belowground measurements—Total soil CO_2 efflux (F_S) was measured at the soil surface near and away from the second tree in each plot using a Li-Cor 6200 infrared gas analyzer (Li-Cor Inc., Lincoln, Nebraska) with a closed cuvette chamber constructed from a PVC pipe for walls, and a Plexiglas top (25.5 cm internal diameter, height at center 13.5 cm). The bottom of the chamber was fitted with a stainless steel edge that was pressed approximately 1 cm into the soil to create a complete seal giving a total system volume of 6300 cm^3 (Selig 2003, Tyree 2005). The machine was calibrated before each sampling date by running a known CO_2 concentration and making necessary adjustments to the IRGA. Between blocks the system was zeroed to account for any drift due to changes in temperature. Respiration measurements were made in the same sequential blocking order at approximately the same time of day for each sampling date. The CO_2 concentration in the cuvette chamber was lowered to ambient atmospheric CO_2 concentration then placed on the soil surface on a spot free of living, photosynthesizing vegetation. After efflux rates began to steadily rise, CO_2 evolution was measured over a 30 second period and respiration rates calculated on a per unit land area.

An index of microbial respiration (R_H) was measured using the LiCor 6250 infrared gas analyzer (Li-Cor Inc., Lincoln, Nebraska) with a 0.25 L cuvette chamber, with a total system volume of 429 cm^3. Four to six cores were taken systematically near and away from trees throughout the plot to a depth of 30 cm (or to depth of water table) with a 2.5 cm diameter pushtube and mixed into a single composite sample. Roots were carefully removed from the soil by hand, and the soil placed into an aluminum weigh boat (10 cm by 2 cm), which was placed into the 0.25 L cuvette chamber (Gough and Seiler 2004, Tyree 2005). Once the CO_2 concentration began to steadily rise (typically within one minute) R_H was measured over a 30 second period. Soil was brought back to the lab, oven-dried for 48 hours at 105 ºC, and weighed gravimetrically to the nearest 0.01g. R_H was calculated and expressed on a per soil mass basis (µmol/kg-soil/min). This was repeated twice in each measurement plot and sub-samples averaged together to arrive at a single R_H value.

Data Analysis

Significant (P = 0.05) treatment (i.e., varietal, LR, fertilization, and interactions) differences were determined by analysis of variance with repeated measures (ANOVARM) using the MIXED procedure in SAS version 9 (SAS. 1999). Covariance structures were selected using Schwarz's Bayesian goodness (BIC) of fit criteria. When necessary individual sampling dates were analyzed using the GLM procedure. Residuals and the normality curves were plotted for all analyses to confirm that data met assumptions of equal variance and normality for all parameters measured. All values are expressed as untransformed averages and standard errors.

RESULTS AND DISCUSSION

Aboveground Measurements

We observed a highly significant (P <.0001) LR by fertilizer by time interaction in aboveground stem volume (fig. 1a). By the end of the second year the addition of LR decreased above ground stem volume by approximately 17 percent relative to control plots. Adding fertilizer resulted in a slight, but non-significant, increase in stem volume when LR was present. We hypothesize the amount of fertilizer added was not enough to overcome any immobilization caused by the addition of high C:N (about 700) LR, but this has yet to be tested. The addition of fertilizer alone resulted in a 40 percent increase in stem volume relative to control plots, which is similar to other first year fertilizer responses in young loblolly pine (Gough and others 2004b, King 2005).

Both varieties showed a decrease in stem volume with the addition of LR, but variety 93 was less inhibited than variety 32 (fig. 1b). Interestingly, both clones responded similarly to fertilizer additions showing no significant fertilizer by variety (P = 0.65), or fertilizer by variety by time (P = 0.99) interactions. This indicates that variety 93 may acquire or utilize N, P, or both more efficiently than Variety 32 when nutrients are limiting, but under conditions where N and P are plentiful varieties 32 shows a slight increase in stem volume. In support of this theory, Li and others (1991) showed that components (uptake and utilization efficiencies) of nitrogen use efficiency (NUE) (stem biomass produced per unit of N applied) in *P. taeda* seedlings were moderately to highly dependent on genotype.

We found no significant difference (P > 0.1) in P_N between LR treatments or varieties. Over all sampling dates there was no fertilizer effect between treatments; however, on a number of dates fertilized plots had significantly greater P_N rates than controls (fig. 2). Slicing the data based on year of needle development showed a significant (P = 0.02) increase in P_N in fertilized plots for needles produced in 2006. In June and December 2006 there were significant (P < 0.05) interactions between fertilizer and variety for P_N. In both instances Variety 93 responding more favorably to fertilization than Variety 32. Similar increases in P_N to fertilization have been shown in loblolly pine (Gough and others 2004b, Samuelson 2000), while others have shown little to no difference (Gough and others 2004a, Maier and others 2002).

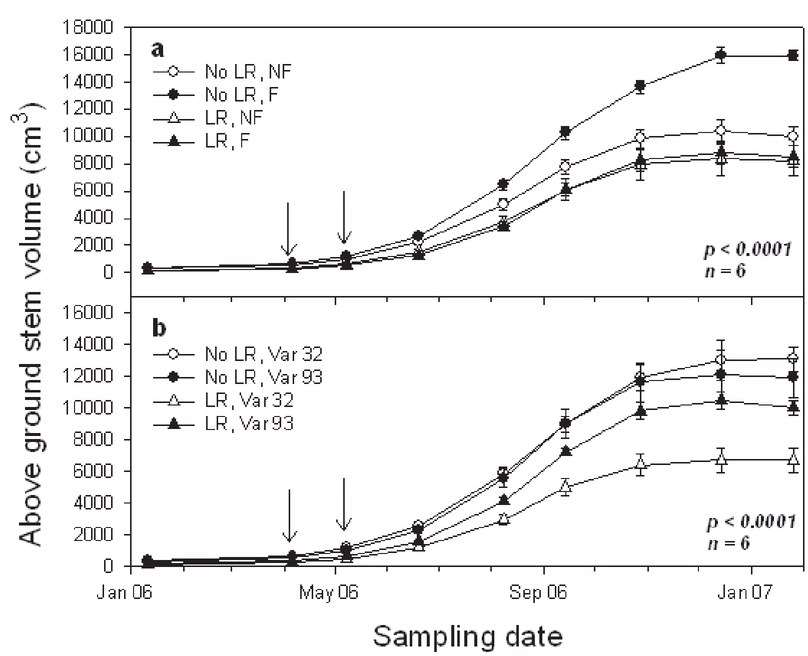

Figure 1—The influence of logging residue (LR) and fertilizer (a), and LR and loblolly pine variety (b) on second year seasonal stem volume (d^2 x ht) in Berkley Co., SC. Arrows indicate time of fertilization and error bars represent ± one standard error from the mean.

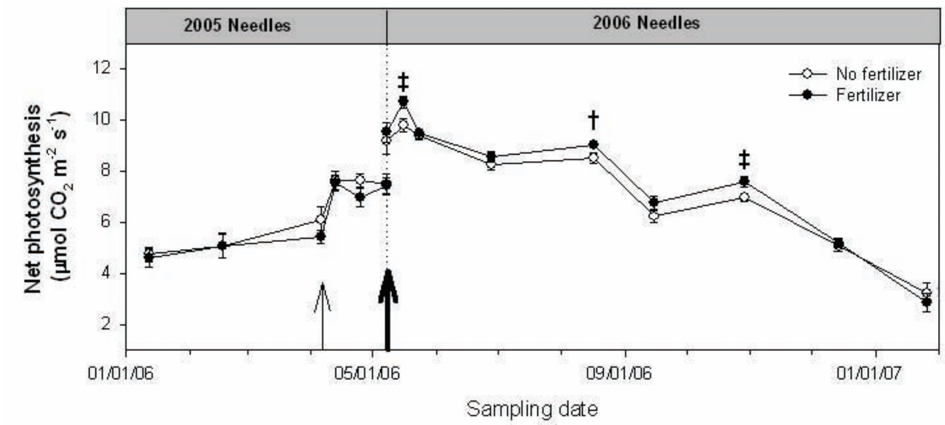

Figure 2—Fertilizer by time interaction for net photosynthesis of most recently elongated, south facing loblolly pine needles measured from January 2006 thru January 2007. Single dagger and double dagger indicate significance at the 0.10 and 0.05 alpha levels, respectively (Error bars show ± 1 standard error from the mean; $n = 12$). Thin and fat arrows indicate times of light and heavy fertilization, respectively.

Belowground Measurements

In contrast to our hypothesis, the addition of LR resulted in no consistent ($P > 0.1$) effect on F_S. We expected that incorporating a readily available source of organic C into the mineral soil would result in a detectable short-term increase in F_S. One implication is that more of the material incorporated may remain in the soil than previously believed potentially leading to increased soil C. Caution is needed when interpreting these results as no estimate of C loss through leaching has been measured on these plots to date. The addition of LR tended to increase R_H, but overall the effect was not statistically significant ($P > 0.1$). Additionally, fertilization with N and P did not result in a consistent effect on F_S. Work by others suggests that an increase in root respiration accompanied by a decrease in microbial respiration may offset each other resulted in no net difference in F_S (Gough and Seiler 2004, Tyree 2005). We did find a tendency for decreased R_H in plots that received fertilizer which has been shown by others in young loblolly pine plantations (Tyree 2005). This finding was significant on three separate sampling dates, but when all the data were analyzed together the effect was not statistically significant ($P > 0.1$).

Variety 32 had consistently ($P = 0.1$) greater F_S rates than Variety 93 throughout the entire 2006 growing season (fig. 3a). What makes this finding remarkable is that this effect was detectable before full occupation of the site by the trees, which implies planting varieties which differ in their allocation patterns may have substantial short-term and possible long-term impacts on NEP. The observed increase in F_S may be a function of increased below-ground C allocation (root mass, exudates) in Variety 32 relative to Variety 93. Support comes from greater R_H ($P = 0.04$) in Variety 32 plots relative to Variety 93 which may be a result of increased exudates (fig. 3b). Further, preliminary findings from a project collaborator using mini-rhizotrons found greater fine-root length in Variety 32 plots (Seth Pritchard, Dept. of Biology, College of Charleston, personal communication), which could impact both increased root exudation and increased root respiration both which would lead to increased F_S.

CONCLUSION

We monitored a number of C fluxes associated to NEP to determine the impacts site C and nutrient manipulations in a young varietal loblolly pine stand over the second growing season. Early results showed LR and fertilization treatments had dramatic effects on above ground C capture as measured by stem volume. Logging residue decreased above ground stem volume by 17 percent by the end of the second growing season, which was presumably due to N immobilization, but the negative effects of LR were much less apparent in plots planted with Variety 93 relative to Variety 32. N and P fertilization alone increased stem volume by 40 percent, which could be a function of observed increases in P_N, increased C allocation to above ground organs, or both. Notably, N and P fertilization was unable to compensate for the reduction in stem volume when LR was present. In contrast to our hypothesis, the incorporation of LR did not result in increased C loss from the soil as measured by F_S implying that more C remained in the soil. We found consistent differences in F_S between varieties. Variety 93 had significantly lower F_S rates than Variety 32, which was surprising at such a young age. This was further supported by a significant decrease in R_H observed in the Variety 93 plots. These early results indicate that LR incorporation along with careful selection of appropriate planting stock may be a viable method for increasing site C.

ACKNOWLEDGMENTS

The authors thank the USDA Forest Service, Agenda 2020 for funding this research and MeadWestvaco for their monumental effort in preparing, maintaining, and providing access to the study site. Specifically, thanks to Steve Patterson and Dr. Phil Dougherty for their technical support. Special thanks to John Peterson, Ben Templeton, and Isaiah Miller for their tireless efforts in the field and lab.

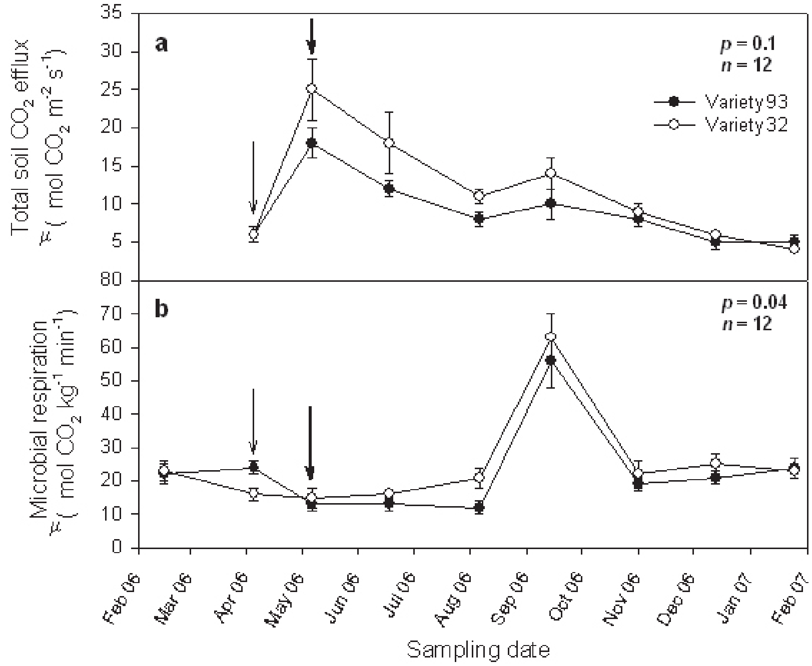

Figure 3—Total soil CO_2 efflux (a) and microbial respiration as influenced by loblolly pine variety (b). Error bars show ± 1 standard error from the mean. Thin and fat arrows indicate times of light and heavy fertilization, respectively.

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