

**SOIL CO₂ EFFLUX AND SOIL CARBON CONTENT AS
INFLUENCED BY THINNING IN LOBLOLLY PINE
PLANTATIONS ON THE PIEDMONT OF VIRGINIA**

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ABSTRACT. The thinning of loblolly pine plantations has a great potential to influence the fluxes and storage of carbon within managed stands. This study looked at the effects of thinning on aboveground carbon and mineral soil carbon storage, 14-years after the thinning of an 8-year-old loblolly pine plantation on the piedmont of Virginia. The study also examined soil respiration for one year following the second thinning of the same stand at age twenty-two. The study was conducted using three replicate .222 hectare stands planted using 3.05 by 3.05 meter spacing in 1980 at the Reynolds Homestead in Critz, VA.

Using two different sample collection methods it was determined that soil carbon was evenly dispersed throughout thinned plots, and that random sampling techniques were adequate for capturing spatial variability. Soil carbon showed a significant negative correlation with soil depth ($p=0.0001$), and by testing the difference between intercepts in this relationship, it was determined that thinning significantly increased soil carbon by 31.9% across all depths ($p=0.0004$). However, after accounting for losses in aboveground wood production, thinning resulted in an overall 10% loss in stand carbon storage. However, this analysis did not take into account the fate of wood products following removal.

Soil respiration, soil temperature, and soil moisture were measured every month for one year near randomly selected stumps and trees. In order to account for spatial variation, split plots were measured at positions adjacent to stumps and 1.5 meters away from stumps. Soil temperature and moisture were both significantly affected by thinning. Regression analysis was performed to determine significant drivers in soil CO₂ efflux. Temperature proved to be the most significant driver of soil respiration, with a positive correlation in thinned and unthinned stands. When modeled using regression, thinning was a significant variable for predicting soil respiration ($p < 0.0009$), but explained only 3.4% of the variation. The effects of thinning were responsible for decreased respiration, however, when coupled with increased temperatures, soil respiration was elevated in thinned stands.

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INTRODUCTION

As atmospheric carbon dioxide increases, there is growing concern over the possibility of global warming caused by greenhouse gases. Carbon dioxide is the most studied and most easily manipulated greenhouse gas, and its concentrations are expected to double by the middle of the 21st century (Allen, 1994). These high concentrations of CO₂ may not only be responsible for increased global temperatures, but erratic weather patterns, and ecological changes as well.

Global concerns about such events prompted a world environmental conference in Kyoto, Japan in 1997. During this conference, several countries including the United States (US) devised a world plan to reduce the emissions of CO₂, as well as capture existing greenhouse gases in order to reduce atmospheric levels. It was decided that individual countries could reduce total CO₂ production through the use of “carbon credits”. These carbon credits will be payments made to industries for the capture and storage of atmospheric carbon into sinks (Bolin, 1998). Even though the US has recently rejected the Kyoto Protocol, it is still very active in the rest of the industrialized world, and it is likely that the US may revisit this world treaty. A limited but initial start at trading carbon has begun with the Chicago Climate Exchange, which is a pilot program for reducing and trading greenhouse gas emissions including those from forest and farm lands (CCE, 2003). Therefore it is important to eventually gain a complete understanding of the global carbon system.

The forest industry is unique in the fact that it has the ability to trap large amounts of CO₂, possibly earning a great deal of carbon credits. Loblolly pine plantations in the southeast cover over 13 million hectares of land and could easily serve as vital sinks (Weir & Greis, 2002). However, for this opportunity to be maximized it is necessary that that these pine ecosystems’ carbon exchange rates be understood and easily predicted. Above ground biomass is already easily measured through leaf litter collection and stem and branch measurements. The readily accessible above ground tree measurements have already led to a good understanding of carbon sequestration and respiration rates in stems

and crowns. Unfortunately, knowledge of below ground activity in the roots is very weak with vast opportunities for advancement in the understanding of sequestration and respiration.

Some work has already been done in this field, and we have a good understanding of how some environmental conditions such as temperature and moisture may affect CO₂ efflux from forest soils. Other studies have also looked at spatial influences on soil respiration. However, it is important to understand what effects different intensive management techniques may have on the carbon cycle in loblolly pine plantations. If this is understood, forest industry will be able to maximize its carbon sequestering by manipulating and ultimately optimizing silvicultural procedures. For instance, certain practices may result in a gain of below ground carbon sequestration, with little to no loss of above ground growth rates.

The thinning of loblolly pine plantations will greatly affect stand carbon dynamics. A variety of components will be affected and their compounded results are unknown. The harvest of trees will likely eliminate root respiration, but the decaying roots of the harvested trees will increase autotrophic respiration. Overall soil respiration rates will be expected to increase as the opening of the stand canopy elevates soil temperature and moisture level. Although most of the root systems from harvested trees will eventually decompose, some carbon may remain in more recalcitrant forms. In the short term, reductions will be seen in above ground carbon capture, but when thinned properly, residual trees will reoccupy the site. It is difficult to predict the results of this complex web of carbon fluxes, but once understood this information could be used in mechanistic process models.

This study will be used in conjunction with several past and current works to help establish a regional model of soil respiration in loblolly pine stands across the southeastern United States. This model will use factors such as stand volume, climate (temperature and moisture), and site productivity to predict stand level soil respiration rates. This particular research project will help to incorporate the effects of thinning into the model.

OBJECTIVES

Main objective: To identify how the thinning of loblolly pine plantations on the piedmont of Virginia affects soil respiration rates. Specifically we will:

- 1.) Determine the effects of thinning on temporal and spatial patterns of soil respiration,
- 2.) Determine the effects thinning has on stored soil carbon.

CHAPTER 1

LITERATURE REVIEW

Global Carbon

At any one time global carbon may be allocated to one of three broad groups, atmospheric, terrestrial, or oceanic carbon. Within these three main groups, carbon may be found in a great variety of forms. Carbon is constantly changing forms and moving through a web of sinks and sources, composing the global carbon cycle.

A sink is an area where carbon may collect, or become trapped for an extended amount of time, as terrestrial or oceanic carbon. A source is a process that moves sequestered carbon back into the atmosphere.

Oceanic Carbon

The oceans of the world contain two main forms of carbon, CO₂ and dissolved carbon in the form of bicarbonate ions. These two forms of oceanic carbon allow the oceans to act as the ultimate sink, containing fifty times more carbon than the atmosphere (>40,000 Gt of carbon) (Trabalka, 1985).

Atmospheric Carbon

Starting in 1958 a continuous record of CO₂ levels has been measured from Mauna Loa, Hawaii, and the South Pole (Houghton et al., 1983). Prior to 1958 measurements were attained from ice cores, moss cores, packrat middens, tree rings, and isotopic measurements of planktonic and benthic foraminifera (Wigley & Schimel, 2000). It has been determined that atmospheric CO₂ fluctuated around 280 ppmv for about 18,000 years until the early 1800's (Houghton et al., 1983). It then started increasing, reaching 356 ppmv in 1993. Atmospheric CO₂ has increased by 15-25% over the past 100 years. It is continuing to increase at a rate of approximately 1.5 ppmv/year (Wigley & Schimel, 2000).

Terrestrial Carbon

Within the terrestrial ecosystem, carbon may be found in vegetation and other living organisms (biota), as well as soil and detritus. Wigley & Schimel (2000) estimate that there are currently 600 Gt of carbon tied up in vegetation. Organic matter in detritus and mineral soil, is the major reservoir of carbon in terrestrial ecosystems (Trumbore et al., 1996). Containing two thirds of all terrestrial carbon, soil is presently storing 1502

Pg ($1\text{Pg} = 1 \times 10^{15} \text{ g}$) of carbon in the upper meter of mineral soil. This is twice the amount of carbon that is in the atmosphere. The second meter contains 491 Pg of carbon and the third meter contains 351 Pg of carbon (Jobbagy and Jackson, 2000). Soil carbon storage is controlled by the balance of carbon inputs from plant production and outputs through decomposition (Schlesinger, 1977).

Total soil carbon can be controlled by a wide variety of factors, but the two most important being climate (Kirschbaum, 1995; Jobbagy & Jackson, 2000) and soil texture (Jobbagy and Jackson, 2000; Silver et al., 2000). Much work has been done to account for carbon allocations within forest soils. Jobbagy & Jackson (2000) estimate that temperate evergreen forests contain 20.4 kg/m^2 of carbon in the first 3 meters of soil, 47% of this carbon may be found in the first 20 cm and 23% from 20-40 cm. Below ground carbon may be in the form of detritus, roots, microbial biomass or mineralized inert soil carbon. In forest ecosystems detrital carbon represents the total carbon in dead organic matter in the forest floor and in the underlying mineral soil layers. Only a small amount of carbon is contained in above ground detritus such as standing dead trees (Schlesinger, 1977). Schlesinger (1977) estimated that temperate pine forests contain 5.6 kg/m^2 of carbon in detritus. Jackson et al. (1996) estimate temperate coniferous forest soils to contain 4.4 kg/m^2 of root biomass, with 52% in the upper 30 cm. Jobbagy & Jackson (2000) estimate 57% of root biomass in the first 20 cm, and 24% from 20-40cm.

Components of CO₂ Efflux

Soil CO₂ efflux, or “soil respiration”, is the combination of heterotrophic and autotrophic respiration. Heterotrophic respiration refers to the CO₂ emitted from microbial activity (decomposition of organic matter) within the soil. Autotrophic respiration is considered to be the sum of direct root and associated rhizosphere organisms’ respiration (Hanson et al., 2000). Global soil respiration rates have been estimated to be between 60-80 Pg (1×10^{15} grams) of carbon / year (Raich and Potter, 1995; Schlesinger, 1977; Raich and Schlesinger, 1992) with an estimated 598 $\text{gC/m}^2/\text{year}$ coming from temperate pine forests (Schlesinger, 1977). These carbon dioxide emissions from soils exceed all other terrestrial atmospheric carbon exchanges with the exception of gross photosynthesis (Raich and Schlesinger 1992).

Several different measurement techniques have been used in an effort to separate microbial respiration from root respiration, including component integration, root exclusion and isotopic approaches. Component integration involves the separation and then individual respiration measurements of roots, sieved soil and litter. Root exclusion is simply the measurement of soil containing roots, and the measurement of an identical soil with no roots. Isotopic methods used for determining the separation of heterotrophic and autotrophic respiration require a more difficult experimental setup; however, it may prove advantageous by eliminating mechanical disturbance of the soil. This method involves the tracing of either radioactive carbon-14 or stable carbon-13 throughout the respiration cycle (Hanson et al., 2000). These methods have produced a wide range of results, establishing that root respiration may account for as little as 10 percent to greater than 90 percent of total soil respiration. This range has been found to be most dependent upon vegetation type and temperature (Hanson et al., 2000; Raich and Tufekcioglu, 2000). For instance, root respiration contributed 50-93% of total soil respiration in cold arctic tundra, 35-62% in pine forests and only 17-40% of in grasslands (Hanson et al., 2000). In 11 year old loblolly pine stands Maier & Kress (2000) noted that root respiration accounted for 20-50% of soil respiration in the top 15 cm of soil, and 50-73% of soil respiration when considering all roots in a 200 cm profile.

Influences on CO₂ Efflux

Soil respiration may be affected by a wide variety of factors. Because soil respiration is the sum of two different entities, every factor's relationship is complicated by interactions between heterotrophic and autotrophic respiration.

Temperature

Temperature is the most recognized and influential control of carbon turnover when moisture is not a limiting factor (Trumbore et al., 1996). Temperature both increases net primary productivity and organic matter decomposition rates, therefore amplifying both microbial and root respiration.

Like many other biological processes, soil respiration's response to temperature may be expressed as a Q_{10} function. Q_{10} may be defined as the ratio of a reaction at a given temperature compared to that reaction at a temperature 10 degrees C warmer. In

general, soil respiration will exhibit a Q_{10} of about 2 (Kirschbaum, 1995). This suggests that on average there will be a two-fold increase in soil respiration for every 10 degree C increase in temperature. Root respiration may demonstrate a Q_{10} as high as 4.6 (Boone et al., 1998). The relative temperature sensitivity of decomposition processes is greater than the temperature sensitivity of net primary productivity (Kirschbaum, 1995). Temperature sensitivity may not be explained by a Q_{10} function across a wide range of temperatures, due to the fact that a combination of biological processes are affected. Soil respiration best follows a Q_{10} function at lower temperatures, especially in tundra and boreal forests (Schlesinger & Andrews, 2000; Kirschbaum, 1995).

Pangle and Seiler (2002) observed a much stronger Q_{10} relationship at lower temperatures in loblolly pine stands. Soil respiration rates exhibited an average Q_{10} of 2.3 for temperatures between 5 and 35 degrees C, however, an average Q_{10} of 3.6 was noted for temperatures between 5 and 15 degrees C. This diminishing effect of temperature was also noted by Boone et al. (1998).

Moisture

While soil respiration's relationship with soil moisture is not as well correlated as with temperature, it still proves to be an important driving factor (Pangle & Seiler, 2002). Rovira (1953) showed that soil respiration has a positive correlation with soil moisture content until near saturation. Soil moisture tends to show a ln-linear relationship with respiration rates. This relationship may vary greatly by soil type because different soils have varying saturation points. As soil approaches saturation, oxygen is unable to move through the soil, making uptake by microorganisms difficult and therefore reducing their ability to create CO_2 . The loss of pore space also makes the escape of CO_2 very difficult (Howard and Howard, 1993). Howard and Howard (1993) found that when moisture content is expressed as a proportion of the soil's water holding capacity, responses for different soil types can be seen over similar ranges.

Kowalenko et al. (1978) found that when soil moisture content is at the other extreme, decreases in soil respiration rates will be seen. Moisture content proves to be a limiting factor in the drier seasons when soils may experience drought conditions, even though temperature is in an optimal range (Pangle & Seiler, 2002). Soil respiration was

found to have a negative correlation with average soil moisture content, ranging from – 0.04 to –0.60 (Pangle & Seiler, 2002).

Spatial variation

Planting density and spatial variation may also exert effects upon soil respiration. Root respiration may be responsible for up to 90% of total soil respiration; therefore CO₂ efflux rates will be influenced by the amount of roots in a given area. Respiration rates at the base of trees were found to be significantly higher than that of the soil away from the trees (Pangle & Seiler 2002; Wiseman, 2001). This effect was even true for very young seedlings (Popescu, 2001). At the stand level this indicates that soil respiration may be higher on sites with higher planting densities and that it will increase as tree root systems reoccupy a harvested or afforested area.

Thinning

Thinning is a commonly used silvicultural procedure in loblolly pine plantations, conducted on over 125,000 hectares of land in the southeast in 2001 (Wear & Greis, 2002). The process involves the systematic harvest of several trees from a young stand, with the intent of reallocating growth from many small trees, to fewer large trees. This practice will invoke both physiological and growth responses for the remaining trees, and micro-climatic changes within the modified stand.

Physiological and growth responses to thinning

Several physiological and morphological changes generally occur following a thinning, and continue changing for many years. Because thinning summons a variety of responses over a large time scale it is easiest to separate the affects into short term and long term responses.

Short Term (1-6 years)

Changes in the appearance of trees may be seen in the first growing season following thinning. Crowns in thinned stands will expand horizontally very quickly, and continue for up to six years. Less canopy competition will allow trees to maintain higher

live crown ratios, since lower crown branches will remain alive. During this time of increased crown expansion individual trees may have twice the litter-fall and double the crown volumes of trees in unthinned stands. Increased light availability to lower crown foliage and subsequent increased photosynthetic rates may be expected for 4 years (Ginn et al., 1991; Peterson et al., 1997).

Five years following the thinning of an eight-year-old loblolly pine plantation in Louisiana, light photosynthetic photo flux density (PPFD) was found to be significantly higher in the lower canopy when compared to unthinned stands. However, these higher light levels were not accompanied by any significant physiological differences between thinned and unthinned stands (Gravatt et al., 1997).

Zhenmin et al. (1999 a) observed that six years following the thinning of a 7-year-old loblolly pine plantation in Louisiana, needle size of the first flush was significantly greater than the unthinned stand. However, shoot elongation was reduced in the thinned stand for both the first and second flushes.

In that same study Zhenmin et al. (1999 b) observed that PPFD was still increased in the lower canopy of the thinned stands six years after thinning. This increased light level in the lower canopy was coupled with a 22-54% increase in photosynthetic rates, as well as increases in transpiration and stomatal conductance to water vapor.

In a study conducted on the piedmont of Virginia, Peterson et al. (1997) found that following thinning the most dramatic changes that occur are in the crown dimensions. Over a 6 year period, following the thinning of 8-year-old loblolly pines, crown diameters of thinned trees increased 82% while unthinned only increased by 20% (Peterson et al., 1997)

Long term

After the initial responses have occurred (6 years), light availability and photosynthetic rates become more similar to the unthinned counterparts (Peterson et al., 1997). By this time other morphological changes may be seen including increased diameter growth and possible increased height, relative to unthinned stands.

It is well documented that growth of individual trees in thinned stands is greater than those in unthinned (Ginn et al, 1991; Della-Bianca & Dils, 1960; Peterson et al., 1997; Hasenauer et al., 1997). Increased diameter growth is expected in all thinning

situations, however, increased height growth is not definite. Height growth as affected by thinning will vary greatly depending on stocking density and site quality (Lohrey, 1977; Zhang et al., 1997).

Hasenauer et al. (1997) and Pienaar et al. (1985) found that basal area development of thinned loblolly pine stands will eventually converge towards that of unthinned stands. Andrulot et al. (1972) found the same volume growth over a fairly wide range of stocking densities on similar sites. All indicating that fewer larger trees may produce the same volume as many small trees.

Thinning and root growth

Excavation of tree roots is a very labor intensive and time-consuming task. Because of this, studies of loblolly pine root systems are relatively rare, especially when compared to the extensive research done on shoot responses to silvicultural treatments (Parker & Van Lear, 1996).

Through core and trench sampling, and more recently the use of air hammers, some data has allowed a glimpse into loblolly pine's root architecture. Mou et al. (1995) provided an estimate of loblolly pine's root/shoot ratio as 0.242, for 3-year-old trees grown in central Alabama. Mou et al. (1995), Parker & Van Lear (1996) and Sword et al. (1996) recognized a significant decrease in root density with increased soil depth. Both coarse and fine roots were concentrated in the upper 10 cm of soil (Mou et al., 1995). In 50-year-old pine plantations located on the upper piedmont of South Carolina, Parker & Van Lear (1996) found that a majority (90%) of the roots located in the first meter of soil were <4mm in diameter.

This vertical distribution of root biomass may vary throughout the growing season. In 10-year-old pine plantation in central Alabama, Sword et al. (1996) found that seasonal trends in soil water content influence root growth. In spring and early summer, root initiation was greatest from 0-5 cm. However, in late summer, root initiation became greater from 15-30 cm, as surface moisture levels decreased.

Thinning is a means of reducing belowground competition between overlapping root systems from adjacent trees. Because of this, thinning will affect root activity through its influence on environmental and physiological variables such as light, mineral

nutrient and water availability, and photosynthate production and partitioning (Santantonio & Santantonio, 1987)

Only one known (to the author) article has been written on root responses to thinning in pine plantations: Santantonio & Santantonio (1987). Because root growth following thinning may greatly affect the amounts of carbon and carbon fluxes, I have chosen to concentrate on effects of comparable manipulations to root growth.

Mou et al. (1995) conducted a study to determine the relationship between aboveground biomass and spatial distributions of roots in loblolly pine plantations. They determined that overall root mass was correlated with aboveground plant mass. Allowing one to infer that increased shoot growth will lead to increased root growth. However, distance-dependent patterns of underground root competition would be difficult to predict on the basis of aboveground biomass alone (Mou et al., 1995). Sword et al. (1996) also concluded that new root growth of young loblolly pine is closely linked to branch phenology and growth.

Santantonio & Santantonio (1987) found that two years following a thinning of 12-year-old *Pinus radiata* in New Zealand, live fine roots (<1mm) were reduced from 1.38 to 0.55 Mg/ha, the standing crop of dead fine roots remained unchanged, and live small roots (1-5mm) declined from 1.03 to 0.54 Mg/ha. The reduction of live roots and unchanged amounts of dead roots suggests that soil respiration may decrease in response to thinning. It is important to note that no attempt was made to determine if live roots collected were from standing trees or harvested trees. Through root grafting it is possible for a portion of a harvested tree's root systems to remain alive. Santantonio & Santantonio (1987) observed several stumps that remained alive 7 years after the original thinning.

Thinning's effects on microclimate

Temporary changes in a stand's microclimate may be seen following a thinning. The creation of gaps in the canopy caused by tree removal will result in increased light availability to both lower branches and the forest floor (Nowak et al., 1991). Della-Bianca and Dils (1960) found that this increased light will be coupled with increased ambient temperatures within the stand and on the forest floor. Reduced root competition

will also increase water availability in the forest soil (Della-Bianca and Dils, 1960). The resultant increased temperatures and increased moisture will interact to greatly increase decomposition rates in the thinned forest floor. This pattern would tend to increase soil respiration following thinning.

Decomposition of roots

Decomposition of roots, like other litter, is influenced by climatic environment as well as substrate quality and the decomposer community (Chen et al., 2000). The thinning of pine plantations temporarily alters the microclimate of the stand until crown closure is again reached, as stated earlier, therefore influencing decomposition.

Increased temperatures, and increased water availability can be expected to increase decomposition rates of the root systems of harvested trees. Elevated temperature is the primary factor responsible for increased decomposition rates (Hornsby et al., 1995). Chen et al. (2000) found that the relative decomposition rates of roots increased with temperature, reaching a maximum at 40 degrees Celsius, then decreasing above that temperature. This decrease in decomposition rate above 40 degrees was attributed to the denaturing of decomposer proteins. The decomposition of roots can be measured on the Q_{10} scale, similarly to total soil respiration. Ruark (1993) identified a Q_{10} of 1.2 and 1.4 for decomposition of small lateral roots of loblolly pine, held for one year at 15 degrees and 25 degrees, respectively. King et al. (1997) experienced alternative findings, stating that temperature and moisture were both of little importance as drivers of decomposition for loblolly pine roots placed in an 8-year-old plantation. These findings may be attributed to the fact that samples were not held at high temperatures or moisture levels continuously for any extended amount of time.

Chen et al. (2000) found a positive correlation between moisture content and decomposition rates of roots of western coniferous trees, with the optimum root moisture content between 100% and 275%. At high moisture contents, rates were more responsive to temperature. Both high and low moisture extremes were found to limit decomposition.

Root size and age can also play an important role in rates of decomposition. Decreases in decomposition rates may be seen with increases in root size (Ludovici et al., 2002). Usman et al. (2000) attributes this to initial nitrogen concentrations in the roots.

King et al. (1997) found that during decomposition the size class of roots significantly affected carbon concentrations as well.

Usman et al. (2000) compared aboveground tissue decomposition to root decomposition in *Pinus roxburghii*. They found that the rate of root decomposition (0.071% of mass per day) was much slower than that of the corresponding aboveground tissue (0.1256%). Using a chronosequence approach Ludovici et al. (2002) estimated that more than 50% of root biomass had decomposed within 10 years of the harvest of 55-70 year old loblolly pines. However, some portions of root systems in this study persisted for 60 years.

Site and climate can clearly affect root decomposition rates, and as stated earlier, thinning as well as other silvicultural practices may alter micro-climate, affecting decomposition. Thinning in *Pinus radiata* has been shown to shorten mean fine-root longevity from 6.2 to 2.5 months (Santantonio & Santantonio, 1987). Ruark (1993) found that 12 months following harvest of a loblolly pine, decomposition of the total root system was 31% and 41% complete at 15 and 25 degrees C, respectively. This suggests that increases in decomposition will be coupled with elevated microbial respiration for at least 12 months following thinning

Effects of clear-cutting on carbon dynamics

No studies known to the author have been conducted on the effects of soil respiration following a thinning, and few have been done on accumulation of carbon in the mineral soil. Therefore, I will concentrate on clear-cutting effects on carbon, as it produces similar belowground and micro-climatic results.

Soil respiration as affected by clear-cutting

Striegl & Wickland (1998) conducted a study on soil respiration following the harvest of mature *Pinus banksiana* in Saskatchewan. They found that CO₂ efflux was reduced in the harvested stand by about 60% for the growing season following harvest. This decrease was observed for several months until emissions equilibrated with the uncut stand for the following winter. Soil respiration is expected to increase substantially in the years following the clear-cut, as decomposition of dead roots begins to occur (Striegl & Wickland, 1998). Results of decreased soil respiration were also found by

Mattson & Swank (1989) in a study conducted on hardwoods in the Southern Appalachians. A 33% reduction in soil respiration was observed on harvested sites. They also determined that the amount of slash remaining on the site did not influence respiration rates. Similar results of decreased soil respiration were observed by Popescu (2001) following the harvest of loblolly pines on the piedmont of Virginia.

Toland & Zak (1994) experienced alternative findings through a study of soil respiration in northern hardwoods following a clear-cut harvest. It was determined that there was no significant difference in respiration rates between harvested and intact stands. These results may be coupled with the findings of Edwards & Ross-Todd (1983) who also found no significant difference between respiration rates of a clear-cut and intact mixed deciduous stand in Tennessee. This lack of difference was attributed to large increases in microbial respiration counter balancing the losses in root respiration.

Residual soil carbon following clear-cutting

Mattson & Swank (1989) found that there were no long-term (5-8 years) changes in soil carbon pools following harvest. Olsson et al. (1996) found that 15-16 years following the clear-cut harvest of coniferous stands in Sweden, overall carbon pools had decreased by 22%-17%. This estimate includes responses in aboveground vegetation, humus and mineral soil pools. While humus and aboveground vegetation pools experienced net losses of carbon, mineral soil exhibited an increase in carbon.

Vesterdal et al. (1995) looked at the effects of thinning on the accumulations of carbon, nitrogen and phosphorus on the forest floor of *Picea abies* stands in Denmark. The study only examined litter, ignoring mineral soil carbon. They found that following thinning there was less accumulation of litter in the humus layer when compared to unthinned stands. This resulted in the conclusion that the total amount of carbon was negatively correlated with thinning intensity.

CHAPTER 2

STORED SOIL CARBON AND COMMERCIAL VOLUME FOURTEEN YEARS AFTER THINNING A LOBLOLLY PINE PLANTATION ON THE VIRGINIA PIEDMONT

Marcus F. Selig

ABSTRACT. The influence that forest management practices may have on carbon storage is becoming ever more important to understand since atmospheric carbon dioxide concentrations continue to increase. The thinning of loblolly pine plantations has a great potential to influence carbon storage through aboveground volume growth and sequestration of carbon into the soil. This study looked at the effects of thinning on aboveground carbon and mineral soil carbon storage, 14-years after the thinning of an 8-year-old loblolly pine plantation on the piedmont of Virginia. Three replicate .222 hectare stands were planted with loblolly pine seedlings using 3.05 by 3.05 meter spacing in 1980 at the Reynolds Homestead Forest Resources Research Center in Critz, VA. Half of each of these stands was thinned in 1988, creating three replicate thinned and unthinned stands. Mineral soil carbon was measured in thinned and unthinned stands in 2002 using two different sample collection methods at depths of 0-10 cm, 10-20 cm, and 20-30 cm. It was determined that soil carbon was uniform throughout thinned plots, and that random sampling techniques were adequate for capturing spatial variability. Soil carbon showed a significant negative correlation with soil depth ($p=0.0001$), and by testing the difference between intercepts in this relationship, it was determined that thinning significantly increased soil carbon by 31.9% across all depths ($p=0.0004$). However, after accounting for losses in aboveground wood production, thinning resulted in a 10% loss in carbon storage for the stand. It is also important to consider the fate and decomposition of wood products, since thinning resulted in large diameter trees and ultimately more saw timber.

INTRODUCTION

Due to concerns over global warming and the possibility of industries buying and selling carbon credits, a great deal of interest has developed with regard to carbon sequestration through forest management. Forest industry is in a unique situation because forest management operations can influence carbon sequestration rates. Practices such as the thinning of pine plantations may increase sequestered carbon in tree biomass, but thinning may also impact long term soil carbon storage.

Soils currently contain two-thirds of all terrestrial carbon, or twice the amount of carbon that is in the atmosphere (Jobbagy and Jackson, 2000). Of that amount, 40% of all belowground carbon is located in forest soils (Dixon et al., 1994). Jobbagy & Jackson (2000) estimate that 70% of the carbon in temperate evergreen forests is located in the top 40 cm of soil, easily within a tree's rooting zone. Therefore, even stand manipulations that only slightly affect soil carbon dynamics have the potential to alter global carbon pools.

Loblolly pine plantations currently occupy over 13 million hectares of land throughout the southeastern United States (Wear & Greis, 2002). Several intermediate operations on these plantations may influence stand carbon dynamics. The thinning process involves the systematic harvest of several trees from a young stand, with the intent of reallocating growth from many small trees, to fewer large trees (Smith et al., 1997). This practice will invoke both physiological and growth responses for the remaining trees and micro-climatic changes within the modified stand (Della-Bianca & Dils, 1960). Remaining trees will have increased growth rates (Ginn et al., 1991; Peterson et al., 1997) with only temporary losses in litter fall and crown volume between thinned and unthinned stands (Vesterdal et al., 1995). Eventually thinned stands' basal area and volume will converge on levels nearly equal to unthinned stands' (Hasenauer et al., 1997; Pienaar et al., 1985) with larger volumes for individual trees.

As stumps and root systems from harvested trees begin to decompose in the newly modified stand, a small percentage of carbon will remain in the mineral soil as humus (Allison, 1973). This organic matter will become more permanently affixed to the soil through a variety of stabilizing mechanisms (Carter and Stewart, 1996). Loblolly

pine root systems have been estimated to maintain between 20-30% of a tree's total biomass (Mou et al., 1995; Van Lear et al., 2000). These large mid-rotation additions of incorporated organic matter to the forest soil clearly have the potential to increase soil carbon across all depths of the rooting zone.

Thinning also serves as a means of reducing belowground competition between overlapping root systems from adjacent trees. Because of this, thinning will affect root activity of remaining trees through its influence on environmental and physiological variables such as light, nutrient, and water availability, and photosynthate production and partitioning (Santantonio & Santantonio, 1987). Thinning may also promote root growth by providing root channels from decomposing roots of harvested stumps. Van Lear et al. (2000) showed that the concentration of resources and low soil strength in root channels from trees harvested 10 years prior provided a favorable rooting environment for remaining trees. These effects will likely result in the rapid reoccupation of the rooting zone by the surviving trees.

The thinning of loblolly pines will therefore result in the addition of dead and decaying stumps to the forest floor, with little or no losses in above or belowground living biomass pools. If root system additions remain in the mineral soil as humus, these additions should be seen as a net gain in ecosystem carbon.

The purpose of this study was evaluate how the silvicultural practice of mid-rotational thinning will affect aboveground carbon sequestration and soil carbon storage 14 years after the thinning of an 8-year old loblolly pine plantation on the piedmont of Virginia. A further objective was to examine soil carbon content as a function of distance from old stumps in order to determine if spatial patterns of soil carbon were evident as a result of thinning.

METHODS AND MATERIALS

Study site and history

The study site is located on the upper piedmont physiographic region at the Reynolds Homestead Forest Resources Research Center in Critz, VA. The area receives an average of 1150 mm of precipitation, maintains an average annual temperature of 14.3 degrees C, a maximum mean temperature of 21.3 degrees C, a minimum annual average of 7.3 degrees C and 260 frost free days extending from mid-March through mid-October (NOAA, 2001).

Historically this land was in agricultural fields, until 1980 when three replicate 0.222-hectare sites were planted with loblolly pine seedlings, using 3.05 by 3.05 meter spacing. Stand one is located on a Lloyd clay loam, a fine, kaolinitic, thermic Rhodic Kanhapludults, and stands two and three are located on a Wickham loam, a fine-loamy, mixed, semiactive, thermic Typic Hapludult. In March of 1988, half of each stand was thinned using a diagonal row thin, removing 49.3 m³/ha, and leaving square spacing of 4.31 meters by 4.31 meters. Crown closure was regained approximately six years after thinning.

Soil carbon sampling and analysis

In March of 2002 soil samples were taken in order to determine the effect of thinning on residual soil carbon. In each treatment one set of samples were taken at 0.3 meter intervals, and two sets of samples were taken at 0.75 meter intervals between trees and old stumps. Samples were taken systematically because a gradient of decreasing soil carbon concentrations with increased distance from old stumps was suspected. Soil samples were taken using a 2-cm diameter push tube. At sampling sites the litter layer was removed and a set of cores were taken from depths of 0-10cm, 10-20 cm, and 20-30 cm. High rock content occasionally made the collection of 20-30 cm impossible.

In thinned treatments, one set of cores was taken at 0.3 meter intervals between one randomly selected tree and corresponding old stump, while at two randomly selected locations samples were taken every 0.75 meters. One set of cores was also taken from the halfway point between the selected tree and its diagonal tree (center) for both

sampling regimes (Fig. 2.1). Samples were taken at 0.3 meter intervals to more precisely determine the effect of the hypothesized gradient. The collection of samples at 0.75 meter intervals therefore allows for fewer numbers of overall samples to be taken, using data from 0.3 meter intervals to interpolate between 0.75 meter interval samples.

In unthinned treatments, one set of cores was taken at 0.3 meter intervals from one randomly selected tree to 1.5 meters from the adjacent tree, while at two randomly selected locations samples were taken every 0.75 meters (Fig 2.2). One set of cores was also taken from the center in both sampling regimes.

This resulted in the collection of 48 sets of cores of samples taken at 0.3 meter intervals, and 42 sets of cores of samples taken at 0.75 meter intervals. Thus, 266 total samples were collected from the three sampled depths. These samples were then dried and passed through a 2mm sieve. All soil that passed through the sieve was bagged and sent to the USDA Forest Service in Research Triangle Park, North Carolina. There, samples were analyzed using a Carlo Erba Nitrogen and Carbon Series II Analyzer (CE Elantech Inc., Lakewood, New York) according to the machines standard operating instructions. Results are given as volumetric percentages of soil carbon.

Soil was also collected using a more traditional transect approach. Five evenly spaced locations along 3 randomly selected transects across each treatment were used. Samples were removed from depths of 0-10 cm, 10-20 cm, and 20-30 cm. The 15 samples from each depth of each treatment were then mixed together thoroughly in a bucket and a single homogenized sample was removed. The 18 samples were then dried and passed through a 2mm sieve. Resultant samples were sent to the USDA Forest Service for analysis.

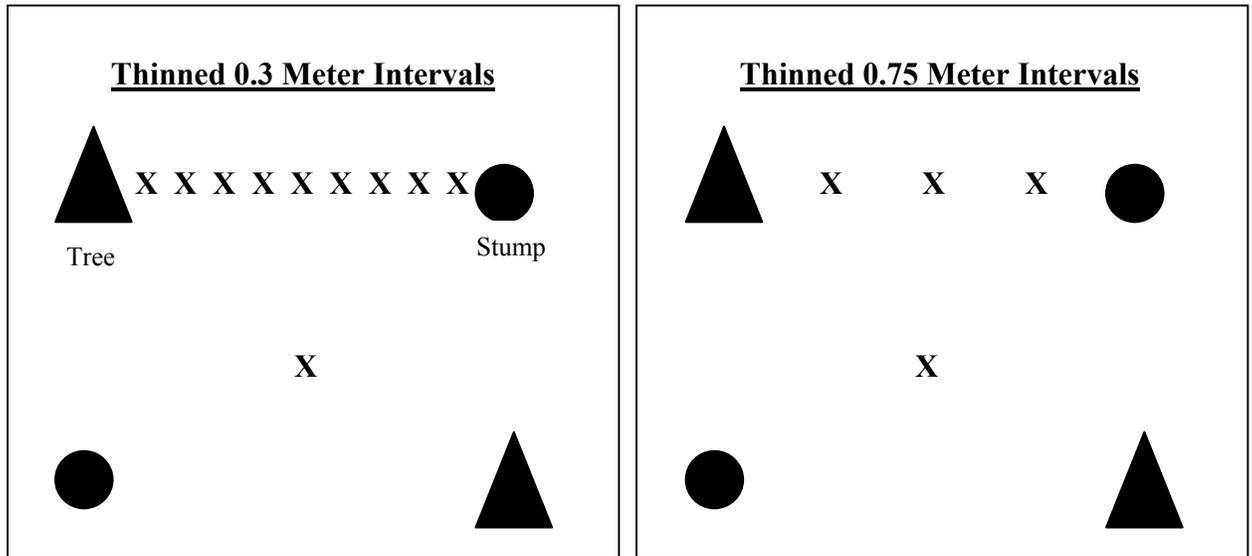


Figure 2.1. Layout of experimental setup for sample collection of soil carbon in thinned treatments of loblolly pine plantations at Reynold’s Homestead.

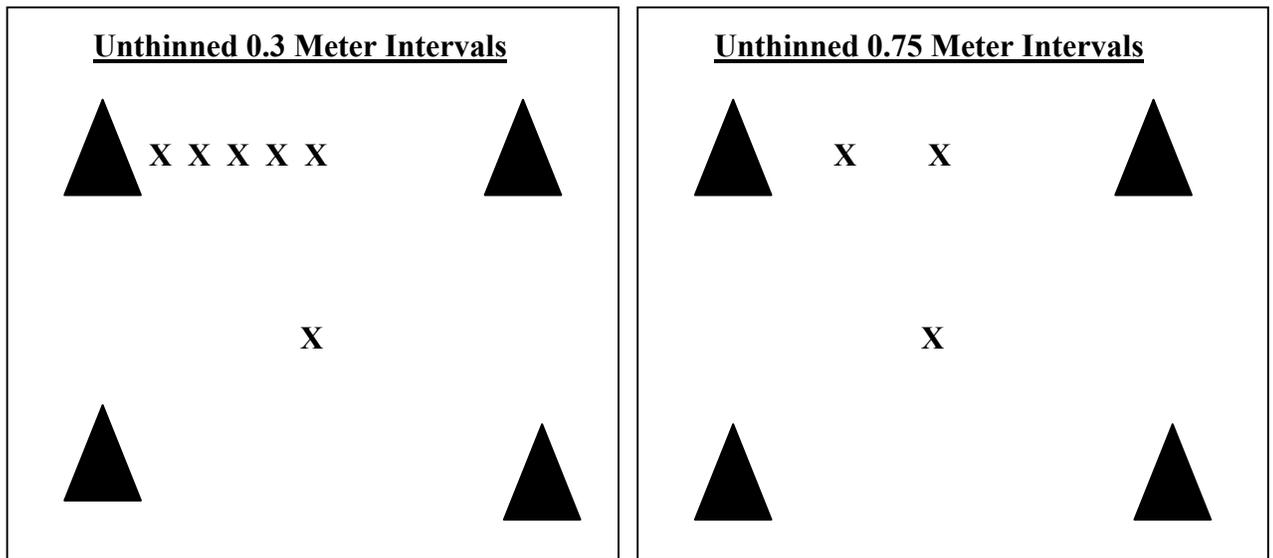


Figure 2.2. Layout of experimental setup for sample collection of soil carbon in unthinned treatments of loblolly pine plantations at Reynold’s Homestead.

Bulk density sampling and analysis

Quantification of the soil bulk density allows carbon volume percentages to be translated into grams of carbon for the soil volume of the entire stand. Bulk density was determined at 0-10cm, 10-20 cm, and 20-30 cm. Bulk density samples were taken at two randomly selected locations within each treatment block. Samples were taken at the three depths using a bulk density slide hammer. This resulted in the collection of 12 sets of depths.

Samples were then dried in an oven at 105 degrees C for approximately 48 hours. After complete drying, the samples were weighed and bulk density was calculated by dividing the dry weight by the volume. Coarse fragments were then removed from the samples and weighed, in order to determine the percentage mass of coarse fragments.

Aboveground volume estimates

Aboveground tree volumes were estimated prior to (1988) thinning and immediately following thinning (Ginn, 1991). In February 2002 diameter at breast height (DBH) was measured using a standard centimeter D-Tape. Total height was measured using a Haglof Vertex III hypsometer (Haglof Inc., Madison, Mississippi). Using these measurements tree volumes were obtained using the formula:

$$\text{Volume} = 0.34864 + 0.00232 (D^2H) \text{ (Burkhart et al., 1977)}$$

Where Volume is in cubic feet, D = diameter at breast height in inches, and H = tree height in feet.

Carbon budget calculations

Total carbon sequestered on the site since planting was calculated by summing residual standing mass of bole wood, the mass of bole wood removed during the 1988 thinning, and the amount of carbon located in the upper 30 centimeters of mineral soil. Aboveground carbon mass was estimated assuming that there are 249.4 kg of carbon per cubic meter of loblolly pine (Birdsey, 1996). Soil carbon mass was calculated using determined volumetric percentages of carbon and respective bulk densities.

Statistical analysis

Carbon data was analyzed using linear regression with the Proc GLM command in SAS V8® (SAS Institute, Cary, North Carolina). Soil depth was used as the independent variable and the square root of percent carbon was used as the response variable. This model was chosen based on its high R-square and appropriateness of fit when compared to actual means. The intercepts of the two treatments were tested against each other to determine significant differences.

In order to determine the effects of the hypothesized gradient in soil carbon with respect to distance from decomposing stumps, data was analyzed using the Proc GLM command in SAS. Distance from the stump was used as the independent variable and percent soil carbon was used as the response variable.

RESULTS & DISCUSSION

Soil carbon sampling methodology

The thinning of loblolly pine stands presented the potential for high variations in soil carbon within a given plot, due to inconsistent distributions of decaying root mass and litter fall. In order to capture suspected spatial variations in soil carbon percentages, a specific methodology was devised for soil field sampling. The use of this systematic gradient for the collection of soil samples showed no discernable trends in soil carbon percentages with regard to distance from old stumps.

Data analyzed from the 266 systematically collected samples resulted in volumetric soil carbon ranging between 0.108% and 5.317% in the thinned stands with an average of 1.169% carbon across all depths. Samples from the unthinned stands ranged between .0124 and 2.997% carbon with an average of 0.965% carbon across all depths. Table 2.1 displays the mean volumetric soil carbon at each of the sampled depths based on the systematic sample collection method.

Soil carbon was unaffected by the proximity of 14-year-old decaying stumps at all sampled depths (Fig 2.3). There is no discernable trend or pattern present that may indicate a soil carbon gradient with respect to distance from decaying stumps or larger root flares.

The average soil carbon content from the transect sampling is illustrated in Table 2.2. The soil carbon patterns are very similar to those found through systematic sampling. Since there was no pattern found between soil carbon and proximity of decaying stumps, these 18 samples were added to the 266 previously collected samples for further data analysis using linear regression.

Table 2.1. Mean soil carbon percentages by soil depth collected from 22-year-old thinned and unthinned loblolly pine plantations on the piedmont of Virginia (266 total samples) using a systematic sampling technique (numbers followed by different letters are significantly different at the 0.10 alpha level).

| Soil Depth (cm) | Soil Carbon | |
|--------------------|----------------|------------------|
| | Thinned (%) | Unthinned (%) |
| 0-10 | 1.855 a | 1.675 a |
| 10-20 | 1.050 b | 0.766 b |
| 20-30 | 0.601 c | 0.464 c |

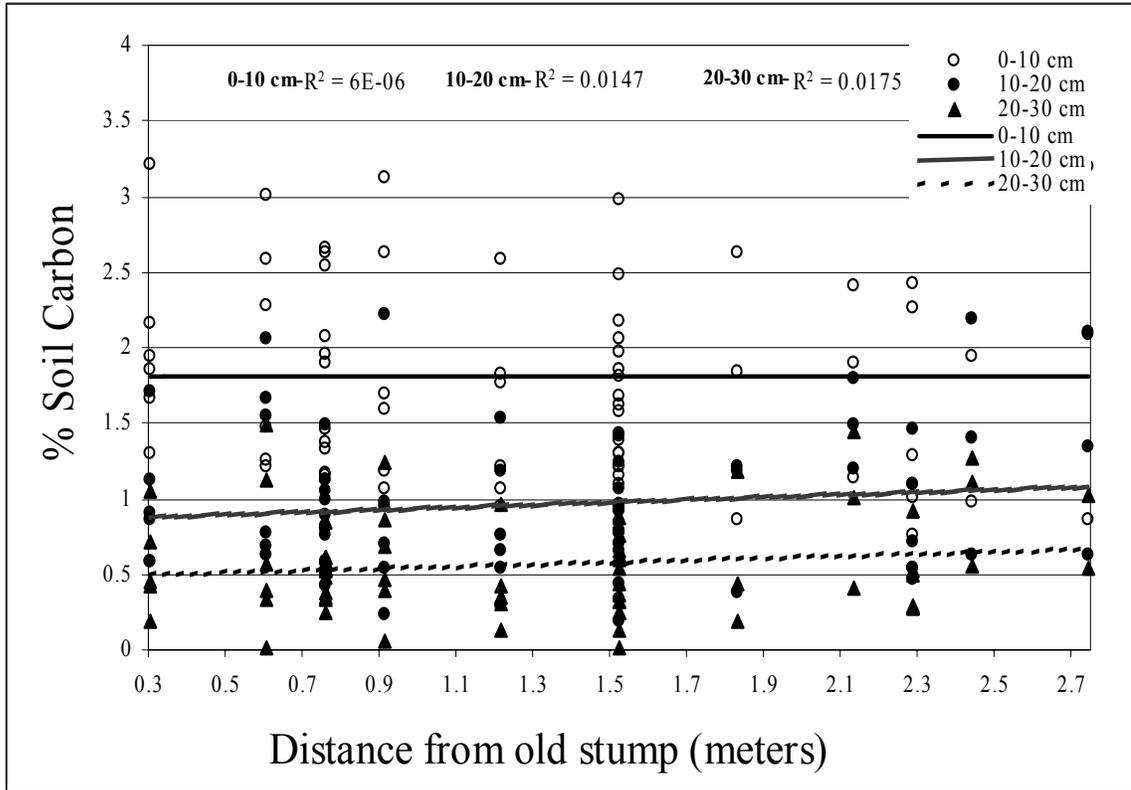


Figure 2.3. Volumetric mineral soil carbon content as affected by depth and distance from decaying stumps, 14-years after the thinning of an eight year old loblolly pine plantation on the piedmont of Virginia.

Table 2.2. Mean soil carbon percentages by soil depth collected from 22-year-old thinned and unthinned loblolly pine plantations on the piedmont of Virginia (18 total samples) using a random sampling technique (numbers followed by different letters are significantly different at the 0.10 alpha level).

| Depth (cm) | Soil Carbon | |
|---------------|----------------|------------------|
| | Thinned (%) | Unthinned (%) |
| 0-10 | 1.868 a | 1.497 a |
| 10-20 | 0.840 b | 0.638 b |
| 20-30 | 0.408 c | 0.289 c |

The uniform distribution of soil carbon throughout thinned pine stands may have been caused through a combination of influences. Root distribution from harvested trees may have been evenly spread throughout the stand by the time of thinning at age eight. Mou et al. (1995) observed some overlap of loblolly pine root systems in the upper soil layers by age three when planted at a density of 4 trees/m². Santantonio & Santantonio (1987) observed some root grafts following the thinning of 12 year old radiata pine, again indicating that root overlap had occurred. Therefore, root decomposition would have equally dispersed soil carbon additions throughout the thinned plots. Another possible influence may have been the complete occupation of the forest floor from opportunistic grasses, herbs and shrubs following thinning. Increased light levels are known to increase understory growth following thinning (Reed & Noble, 1994; Wetzel & Burgess, 2001), however once canopy closure is regained these light dependent species will die off and incorporate themselves into the soil. Complete occupation of the forest floor following thinning would therefore result in even additions of soil carbon.

The homogenous distribution of soil carbon following thinning therefore allows for a more random sampling method. Our results indicate the more commonly used grid or transect sampling techniques would be sufficient to determine soil carbon fluctuations following thinning.

Effects of depth and thinning on soil carbon

A regression model was developed to predict soil carbon for the treatments using depth as a dependent variable (284 total samples). Testing the intercepts for predicted soil carbon of thinned and unthinned stands, showed that thinned stands maintained significantly higher soil carbon percentages ($p=0.0004$) (Fig. 2.4). Analyzed data showed a significant ($p < 0.0001$) negative correlation between depth and soil carbon in both thinned and unthinned stands (Fig. 2.4).

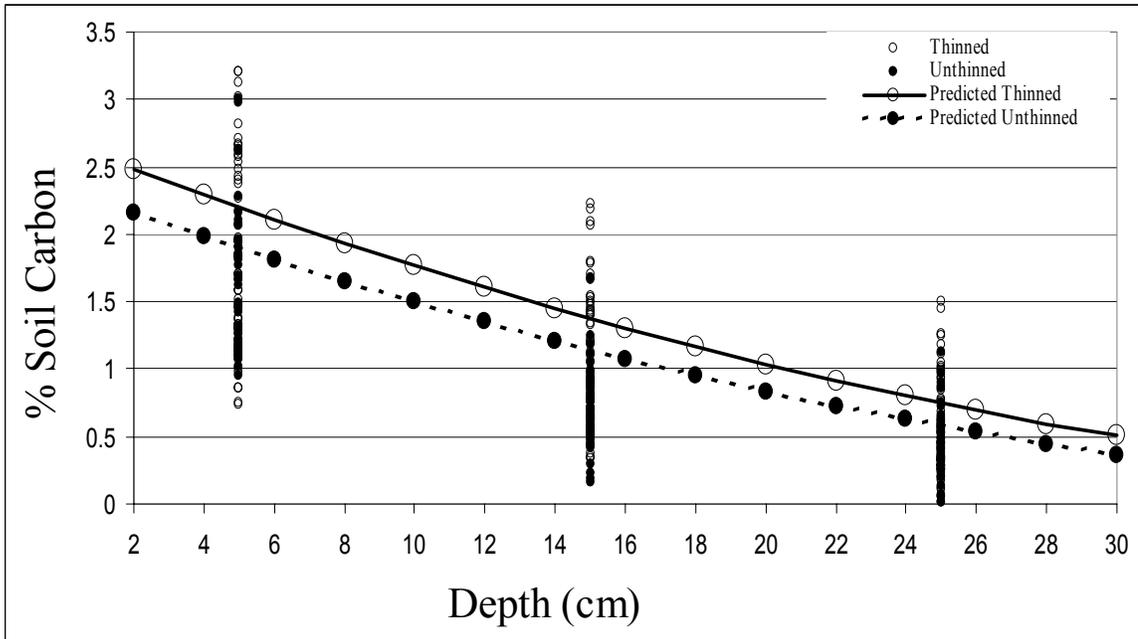


Figure 2.4. Volumetric mineral soil carbon as affected by thinning and depth on a 22-year-old loblolly pine plantation on the piedmont of Virginia (intercepts $p = 0.0004$) (284 total samples).

In both thinned and unthinned stands soil carbon had a significantly negative correlation with sampling depth ($p = 0.0001$). This relationship has been consistently noted (Jobbagy & Jackson, 2000). Constant additions to the litter layer of the forest floor and loblolly pine's concentrated root distribution in the top 10 cm of soil (Mou et al., 1995; Parker & Van Lear, 1996; Sword et al., 1996) presents higher carbon additions to the soil surface (Jobbagy & Jackson, 2000). As the carbon is incorporated into the soil and leached through the horizons the amount of carbon present will begin to be reduced (Jobbagy & Jackson, 2000), providing a decreasing gradient in soil carbon with depth.

It was determined that soil carbon percentages were significantly increased ($p = .0004$) by 31.9%, fourteen years following thinning. Because no known previous work has assessed mineral soil carbon fluctuations following thinnings, our results may only be compared to the effects of clear-cutting on residual soil carbon, which appears to have a wide range of effects. Mattson & Swank (1989), as well as Huntington & Ryan (1990) observed no change in mineral soil carbon 5-8 years and 3 years respectively following clear-cuts. Black & Harden (1995) observed 17 years of decreasing soil carbon following the clear-cut of a mixed conifer forest in California. However, Olsson et al. (1996) noted increases in mineral soil carbon 15-16 years post harvest.

The observed increases in soil carbon following thinning may be attributed to a variety of factors. There were two large additions of organic matter to the soil of the thinned stands, which unthinned stands did not receive. One addition was the decomposition of root systems from harvested trees and the second was the growth, death, and decomposition of opportunistic understory species following thinning (Reed & Noble, 1994; Wetzel & Burgess, 2001). Assuming that no root grafting occurred, the harvested root systems partially decayed over the 14 years since harvest, leaving a percentage of their mass as mineral soil carbon (Allison, 1973). Ludovici et al. (2002) observed that within 10 years following the harvest of 55-70 year old loblolly pines, over 50% of root biomass had decomposed. The vertical distribution of the roots, as noted by Parker & Van Lear (1996), likely allowed the additions of carbon to be observed across all sampled depths. The growth of a light dependent understory upon canopy removal as noted by Reed & Noble (1994) and Wetzel & Burgess (2001) provided another source of possible carbon to the forest soil. As canopy closure was regained approximately six

years after harvest (Peterson et al., 1997), the needed light was likely restricted, causing the death of various herbaceous species followed by their decomposition and incorporation into the mineral soil.

These two additions of organic matter were coupled with only temporary losses of carbon from litterfall (Vesterdal et al., 1995), and possible increased growth from remaining root systems (Van Lear et al., 2000). These two processes are major reasons why thinning's affects on soil carbon would not parallel those of clear-cutting's affects. Clear-cut pine stands will be expected to lose all existing litter fall, and root growth.

Bulk density and total soil carbon

In order to determine the mass of carbon stored in the soil following thinning, it is necessary to obtain bulk density measurements. Bulk density was found to be unaffected by depth and thinning, averaging 1.425 g/cm^2 (Table 2.3). Using predicted soil carbon concentrations and the mean bulk density by treatment and depth, the mass of soil carbon was estimated for 0-30 cm. Soil of thinned stands maintained 45.5 metric tons of carbon per hectare, while the soil of unthinned stands maintained 34.5 metric tons of carbon per hectare. This is a 31.9 % increase in soil carbon gained by thinning.

Aboveground volume estimates

Fourteen years after thinning, thinned stands were carrying $569 \text{ m}^3/\text{ha}$ and unthinned stands maintained $751 \text{ m}^3/\text{ha}$. The average diameter at breast height in thinned stands was 32.0 cm, compared to 25.6 cm in unthinned stands. With half as many trees, thinned stands maintained a basal area of $43.5 \text{ m}^2/\text{ha}$, and unthinned stands $54.6 \text{ m}^2/\text{ha}$. Mean height of thinned stands was 20.4 meters and unthinned stands was 21 meters (Table 2.4).

Unthinned stands suffered from unusually low mortality and had negligible understory competition. This may have contributed to these exceedingly high volume estimates for loblolly pine on the piedmont of Virginia.

Table 2.3. Mean soil bulk density of 22-year-old thinned and unthinned loblolly pine plantations on the piedmont of Virginia.

| Depth (cm) | Bulk Density | |
|---------------|---------------------------------|-----------------------------------|
| | Thinned (g/cm ³) | Unthinned (g/cm ³) |
| 0-10 | 1.423 | 1.418 |
| 10-20 | 1.340 | 1.474 |
| 20-30 | 1.427 | 1.471 |

Table 2.4. Mean diameter, height and volumes of thinned and unthinned stands of loblolly pine on the piedmont of Virginia, prior to thinning, immediately following thinning, and prior to soil sampling.

| | Diameter (cm) | | Height (m) | | Volume (m ³ /ha) | |
|--------------------|---------------|-----------|------------|-----------|-----------------------------|-----------|
| | Thinned | Unthinned | Thinned | Unthinned | Thinned | Unthinned |
| 1988 pre-thinning | 14.6 | 13.9 | 8.75 | 8.35 | 98.6 | 85.3 |
| 1988 post-thinning | 14.6 | 13.9 | 8.75 | 8.35 | 49.3 | 85.3 |
| 2002 | 32.0 | 25.6 | 20.40 | 21.00 | 569.0 | 751.0 |

Fourteen years after thinning, thinned stands were carrying 75.8% of the volume and 79.6% of the basal area of the unthinned stands, with half the number of trees. Mean tree diameter increased 20% with only a slight loss in mean height. The observed individual tree growth as well as stand volume and basal area are within the expected range, as observed by Hasenauer et al. (1997) after a similar thinning regime. Lohrey (1977) noted that thinned loblolly pine stands under a similar regime would come to within 90% of the volume of unthinned stands by age sixteen. The larger observed gap, when compared to Lohrey (1977), between thinned and unthinned stands was likely due to the extremely low mortality rate of trees in unthinned stands. Only one to two measurement trees per plot were no longer living by twenty-two years of age, as compared to the near 40% mortality experienced by Lohrey (1977).

Carbon budget

By accounting for the amount of carbon (bole wood) removed by the thinning in 1988, the amount of standing volume remaining in the stands, and the amount of carbon stored in the mineral soil, we were able to develop a carbon storage budget for thinned and unthinned loblolly pine plantations on the piedmont of Virginia over a 22 year rotation. This budget explains that thinning stored 199.7 metric tons of carbon/ha, while unthinned stands stored 221.8 metric tons of carbon/ha (Fig. 2.5). This 10% loss in carbon storage explains that the gains in carbon storage made through mineral soil, do not compensate for the losses in aboveground biomass over the 22-year rotation.

When calculating a complete carbon budget it is important to consider the ultimate fate of wood removed from the managed site. Since thinning increases the final size class distribution of standing trees, more wood is available for saw timber production. Spinney (2002) determined that management regimes favoring saw timber production store more carbon for a longer period of time in the final product.

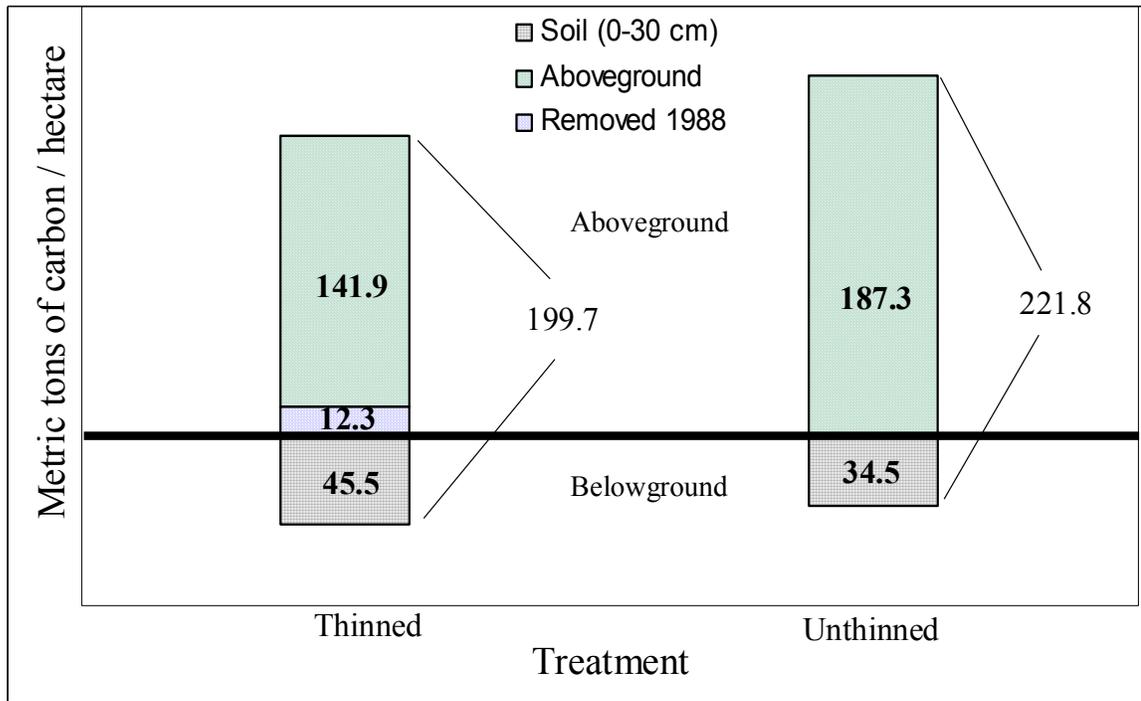


Figure 2.5. Carbon allocation in commercial loblolly pine wood and mineral soil 14 years after the thinning of an 8-year-old loblolly pine plantation on the piedmont of Virginia.

CONCLUSIONS

The purpose of this study was evaluate how the common silvicultural practice of mid-rotational thinning will affect aboveground carbon sequestration and soil carbon storage 14 years after the pre-commercial thinning of an 8-year old loblolly pine plantation on the piedmont of Virginia. A further objective was to examine soil carbon content as a function of distance from old stumps in order to determine if spatial patterns of soil carbon were evident as a result of thinning.

Sampling soil carbon fourteen years after the thinning revealed a 31.9% increase in mineral soil carbon to a depth of 30 cm. Using two different sampling techniques, it was shown that soil carbon was evenly distributed throughout thinned stands, and negatively correlated with soil depth.

Observed increases of soil carbon in thinned stands were counterbalanced by decreases in aboveground volume production. When soil carbon volumes and aboveground commercial volumes were combined, thinning resulted in a 10% loss in stored carbon in the stand. To truly determine the effects of thinning on carbon storage it will also be important to examine storage brought about by final product alterations caused by thinning, and carbon costs induced by intermediate operations.

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CHAPTER 3

SOIL RESPIRATION AS AFFECTED BY THE THINNING OF A 22-YEAR-OLD LOBLOLLY PINE PLANTATION ON THE VIRGINIA PIEDMONT

Marcus F. Selig

ABSTRACT. Covering over 13 million hectare in the southeastern US, loblolly pine plantations release significant amounts of CO₂ through soil respiration. These respiration rates may be altered through the common silvicultural practice of thinning. To better understand the affects of thinning on soil respiration, 3 replicates of 22-year-old thinned and unthinned loblolly pine plantations on the piedmont of Virginia were monitored for one year following thinning to a spacing of 6.1 by 6.1 meters. Soil respiration, soil temperature, and soil moisture were measured every month for one year. Measurements were taken in thinned stands near newly cut stumps, stumps from a previous (1988) thinning, and residual trees. In unthinned stands measurements were taken with respect to standing trees. In order to account for spatial variation, split plots were measured at positions adjacent to stumps and 1.5 meters away from stumps. Soil respiration ranged from an average of 1.189 in March to 6.908 $\mu\text{molCO}_2/\text{m}^2/\text{sec}$ in September. Respiration of unthinned stands ranged from an average of 0.9124 in March to 6.614 $\mu\text{molCO}_2/\text{m}^2/\text{sec}$ in September. Soil temperature and moisture were both significantly affected by thinning. Regression analysis was performed to determine significant drivers in soil CO₂ efflux. Temperature proved to be the most significant driver of soil respiration, with a positive correlation in thinned and unthinned stands. When modeled using regression, thinning was a significant variable for predicting soil respiration ($p < 0.0009$), but explained only 3.4% of the variation.

INTRODUCTION

Consideration of rising atmospheric CO₂ and its possible affects on global warming have prompted interest into the sources and sinks of global carbon pools. Forest soils are both a sink and source of global carbon, storing carbon as living organic matter (roots and biota), detritus, and mineral soil carbon (Trumbore et al., 1996). Soil currently contains two thirds of all terrestrial carbon; this is twice the amount of carbon that is in the atmosphere (Jobbagy and Jackson, 2000). Of that amount, 40% of all belowground carbon is located in forest soils (Dixon et al., 1994).

Forest soils may also serve as a source of atmospheric CO₂ through the process of soil respiration (E_c). This is the combination of heterotrophic and autotrophic respiration. Heterotrophic respiration refers to the CO₂ emitted from microbial activity (decomposition of organic matter) within the soil. Autotrophic respiration is considered to be the sum of direct root and associated microbial rhizosphere respiration (Hanson et al., 2000). Global E_c rates have been estimated to be between 60-80 Pg (1 x 10¹⁵ grams) of carbon / year (Raich and Potter, 1995; Schlesinger, 1977; Raich and Schlesinger, 1992) with an estimated 598 gC/m²/year coming from temperate pine forests (Schlesinger, 1977). These carbon dioxide emissions from soils exceed all other terrestrial atmospheric carbon exchanges with the exception of gross photosynthesis (Raich and Schlesinger, 1992).

It is already known that E_c may be affected by a wide variety of factors. Because E_c is the sum of two different entities, every factor's relationship is complicated by interactions between heterotrophic and autotrophic respiration. Temperature is the most recognized and influential control of carbon turnover when moisture is not a limiting factor (Trumbore et al., 1996). Temperature increases both net primary productivity and organic matter decomposition rates, therefore amplifying both microbial and root respiration.

While E_c's relationship with soil moisture is not as well correlated as with temperature, it still proves to be an important driving factor (Pangle & Seiler, 2002). Pangle & Seiler (2002) found that soil moisture's influence on soil respiration was small, except during times of drought, when soil moisture became the most critical factor

affecting soil respiration. Rovira (1953) showed that E_c has a positive correlation with soil moisture content until near saturation.

Planting density and spatial variation may also affect E_c . Root respiration may be responsible for up to 90% of total E_c ; therefore E_c rates will be influenced by the amount of roots in a given area. Respiration rates at the base of trees were found to be significantly higher than that of the soil away from the trees (Pangle & Seiler, 2002). This was found to be true in newly planted seedlings (Popescu, 2001), to over 20-year-old trees (Wiseman, 2001).

Over 13 million hectares of forest soils in the southeastern United States are currently covered with loblolly pine plantations (Wear & Greis, 2002). Forest operations have the ability to affect carbon dynamics within these managed stands, by altering growth and decomposition above and below ground. Thinning is a commonly used silvicultural procedure, conducted on over 125,000 hectares of land in the southeast in 2001 (Wear & Greis, 2002). The process involves the systematic harvest of several trees from a young stand, with the intent of reallocating growth from many small trees, to fewer large trees (Smith et al., 1997). This practice will invoke both physiological and growth responses for the remaining trees and micro-climatic changes within the modified stand (Della-Bianca & Dils, 1960). Remaining trees will have increased growth rates with only temporary losses in litter fall and crown volume between thinned and unthinned stands (Ginn et al., 1991; Peterson et al., 1997). Eventually thinned stands' basal area and volume will converge on levels equal to unthinned stands' (Hasenauer et al., 1997; Pienaar et al., 1985).

As stumps and root systems from harvested trees sit in the newly modified stand, increased forest floor temperatures and soil moisture will begin to decompose the belowground biomass (Nowak et al., 1991; Della-Bianca and Dils, 1960). These new additions of decomposable material to the forest soil will likely increase heterotrophic respiration. Thinning will affect root activity of remaining trees through its influence on environmental and physiological variables such as light, mineral nutrient and water availability, and photosynthate production and partitioning (Santantonio & Santantonio, 1987). Thinning may also help promote root growth by providing root channels from decomposing roots of harvested stumps. Van Lear et al. (2000) showed that the

concentration of resources and low soil strength in root channels from trees harvested 10 years prior provided a favorable rooting environment for remaining trees.

These events will lead to a complex mix of CO₂ fluxes from the soil. Roots systems of harvested trees will likely die, unless grafting occurs, reducing autotrophic respiration. Remaining trees will likely increase root growth and respiration, reoccupying the site. Temporary autotrophic respiration additions may also be seen from root systems of advantageous understory growth. Decomposition of old roots will also likely increase heterotrophic respiration rates.

The purpose of this study was to determine how the thinning of a 22-year old loblolly pine plantation on the piedmont of Virginia affected E_c over the course of one year following harvest. Both temporal and spatial patterns as affected by thinning were investigated.

METHODS AND MATERIALS

Study site and history

The study site is located on the upper piedmont at the Reynolds Homestead Forest Resources Research Center in Critz, VA. The area receives an average of 1150 mm of precipitation, maintains an average annual temperature of 14.3 degrees C, a maximum mean temperature of 21.3 degrees C, a minimum annual average of 7.3 degrees C and 260 frost free days extending from mid-March through mid-October (NOAA, 2001).

Historically this land was in agricultural fields, until 1980 when three replicate 0.222-hectare sites were planted with loblolly pine seedlings, using 3.05 by 3.05 meter spacing. Stand one is located on a Lloyd clay loam, a fine, kaolinitic, thermic Rhodic Kanhapludult, and stands two and three are located on a Wickham loam, a fine-loamy, mixed, semiactive, thermic Typic Hapludult. In March of 1988, half of each stand was diagonally row thinned, leaving square spacing of 4.31 meters by 4.31 meters. Crown closure was reached again approximately six years after the thinning.

The thinned section of the stand was thinned again in April of 2002 by the removal of every other row of trees. A majority of the slash was removed from the site. The resultant treatment then contained 22-year-old loblolly pines at 6.1 by 6.1 meter spacing, and a mix of new and old stumps. Following the second thinning, thinned stands

had a basal area of 23.0, 20.8 and 18.9 m²/hectare while unthinned stands maintained 55.1, 59.0 and 49.7 m²/hectare in blocks one, two and three respectively.

Experimental layout

Past studies (Pangle and Seiler, 2002; Wiseman, 2001) have revealed a strong measurement position effect on E_c . Measurements taken near trees have significantly higher rates. Therefore, to adequately characterize the spatial effects of thinning on E_c , measurements were taken both near and away (1.5 meters away) from thinned trees, new stumps and old (1988 thinning) stumps. In the unthinned treatment, measurements were taken near and away from trees. Four locations in each treatment were identified and measured and used as subsamples. Near and away positions were analyzed in the analysis as a split. For each measurement period, E_c was measured at the same general location although not at the exact spot.

Soil respiration measurements

Respiration measurements were taken monthly beginning in February of 2002, two months prior to thinning. Following the thinning in April, monthly measurements were taken for one year. E_c was measured using the LiCor 6200 infrared gas analyzer (LiCor Inc., Lincoln, Nebraska). A dynamic closed cuvette chamber system was used in conjunction with the LiCor 6200. The cuvette chamber was constructed using PVC piping for walls, a plexi-glass top, and an aluminum edge on the bottom. The chamber has an internal diameter of 25.5 cm, stands 13.5 cm tall, and has an entire system volume of 6744 cm³. The aluminum edge on the bottom of the chamber will allow it to cut through needles on the forest floor, reducing error imposed by sub-litter airflow caused by windy conditions.

The chamber was attached to the LiCor 6200 using 0.32 cm diameter plastic tubing. The input hose enters into the wall of the chamber, where air will then be diffused around the internal circumference through a perforated hose surrounding the inner wall. The suction hose enters the chamber through a connection in the plexi-glass top.

The LiCor 6200 was recalibrated before every day of data collection. The system was zeroed before data collection at every block. Measurements were taken at the base

of the tree, new stump, or old stump, and approximately 1.5 meters away from the object. Care was taken to place the chamber on bare forest floor, as photosynthesizing vegetation will alter E_c measurements.

Respiration rates were determined by measuring E_c for a continuous 30-second period. The LiCor 6200 then calculated the E_c rate using equation 1:

$$\text{Soil } E_c = [(\Delta C/\Delta t)(PV_t/RT)] / \text{Area} \quad \text{Equation 1}$$

Where $C = [\text{CO}_2]$, $t = \text{time (30 seconds)}$, $P = \text{atmospheric pressure}$, $V_t = \text{system volume}$, $R = \text{universal gas constant}$, and $T = \text{temperature}$.

Soil moisture and temperature measurements

Soil moisture and temperature were measured concurrently with E_c . Soil moisture was measured to a depth of 12 cm using a HydroSense moisture meter (Campbell Scientific, Australia). Measurements are expressed as a volume percent. Temperature was measured to a depth of approximately 7 cm using a Digi-sense temperature gauge (Cole-Parmer Instrument Co., Niles, Illinois), and expressed to the nearest 0.1 degree C.

Statistical analysis

The effect of thinning and measurement location (new stump, old 1988 thinned stump, tree) on E_c was analyzed for each sampling date separately. Analysis of variance (ANOVA) was performed using a split-block design using JMP IN® statistical discovery software Version 4 (SAS Institute, Cary, North Carolina). Two analyses were performed. In one analysis, E_c of thinned trees, unthinned trees, new stumps, and old stumps were compared separately for each sampling date. In a second analysis, thinned and unthinned average E_c was compared. Soil temperature was later added to each model as a covariate to determine if differences found were due primarily to changes in soil temperature (See Appendix).

Using SAS V8 (SAS Institute, Cary, North Carolina) the data set for the one-year period was then analyzed using linear regression. The analysis was used to determine the

significance of the relationship between E_c and soil temperature, soil moisture, treatment, measurement location, and measurement position. Significant variables and interactions included in the regression models were selected to achieve models with a high R-square and low Cp statistic.

RESULTS

Effect of treatment and position on soil respiration

Over the 12 month period E_c in thinned stands ranged from an average of 1.189 in March to 6.908 $\mu\text{molCO}_2/\text{m}^2/\text{sec}$ in September. E_c of unthinned stands ranged from an average of 0.9124 in March to 6.614 $\mu\text{molCO}_2/\text{m}^2/\text{sec}$ in September.

E_c was higher in thinned stands on eight out of twelve sampling dates, but was only significantly higher on three of those eight dates ($p < 0.10$) (Fig. 3.1). E_c was higher in the thinned stands on all three of the significant dates. When soil temperature was used as a covariate in the ANOVA for the three significant dates, the difference between the thinned and unthinned stands became insignificant.

Figure 3.2 illustrates that there is no discernable pattern or significant difference in E_c between the new stumps, 14-year-old stumps, trees in the thinned stands, and trees in the unthinned stands on any date. Over the course of one year, mean respiration was 3.369, 2.738, and 3.232 $\mu\text{molCO}_2/\text{m}^2/\text{sec}$ for newly cut stumps, old stumps, and trees in thinned stands respectively. This figure also illustrates the high variability between the different measurement plots within the thinned stands.

While near measurements were consistently higher on all measurement dates, position had a significant affect on E_c on only three out of the twelve sampling dates, April, 2002, June, and July (Fig. 3.3). To further investigate the effects of position on soil respiration, data was separated between thinned and unthinned stands. This data showed that in thinned stands, mean E_c was greater at the near position on all twelve of the sampling dates, and significantly greater for the June and January measurement dates ($p < 0.10$) (Fig. 3.4). Unthinned stands maintained higher E_c at the near position on eleven of the twelve sampling dates, being significantly higher on the April, 2002, and June measurement dates ($p < 0.10$) (Fig. 3.4).

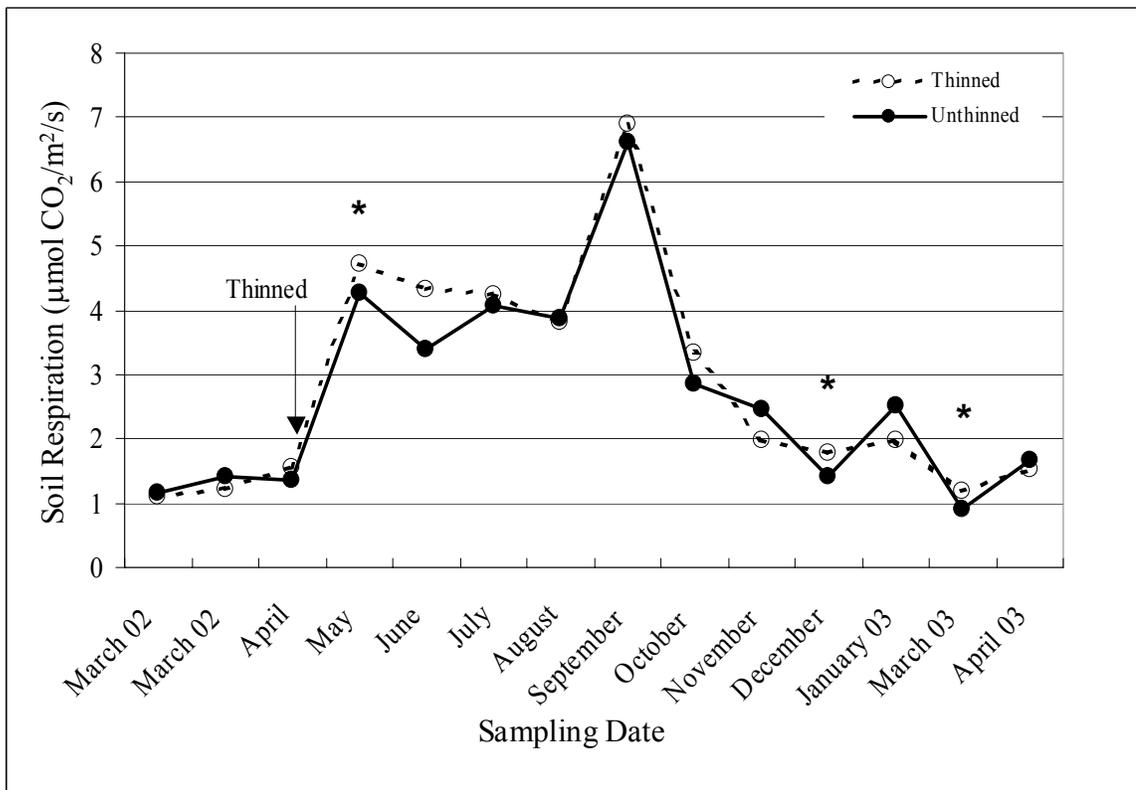


Figure 3.1. Soil respiration as affected by the thinning of a 22-year-old loblolly pine plantation on the piedmont of Virginia, sampled over the course of one year following thinning. An asterisk denotes a significant difference between thinned and unthinned stands ($p < 0.10$)

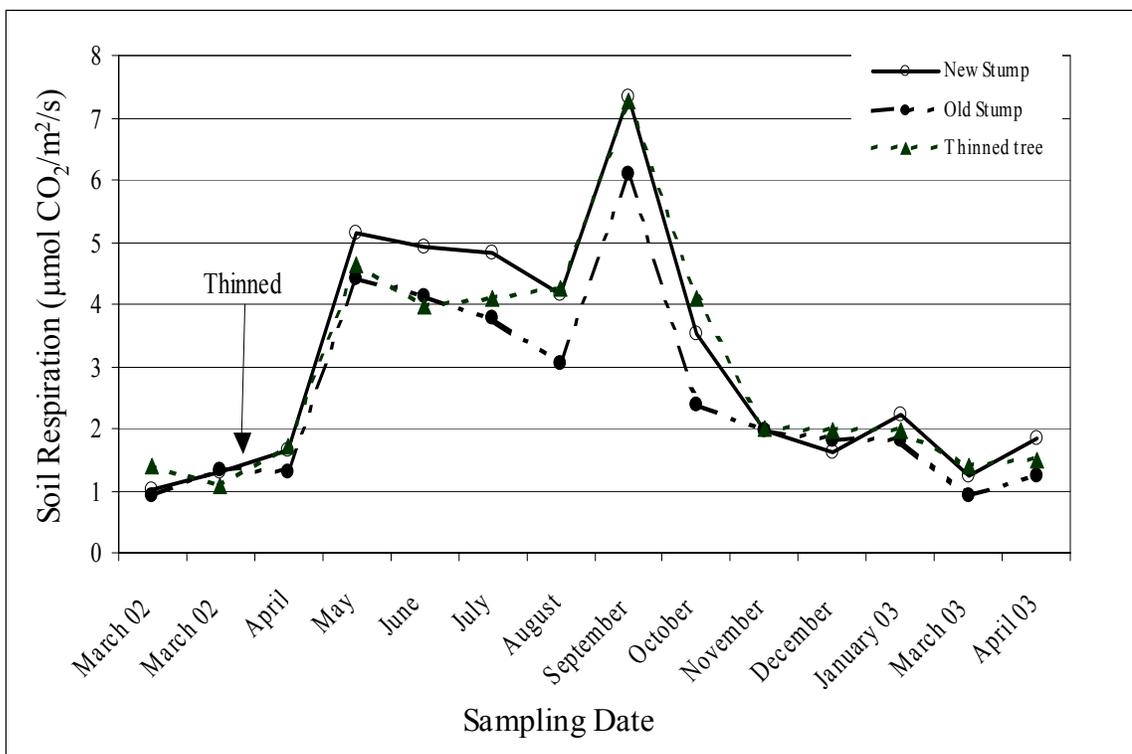


Figure 3.2. Effect of measurement location on soil respiration following the second thinning of a 22-year-old loblolly pine plantation on the piedmont of Virginia, sampled over the course of one year.

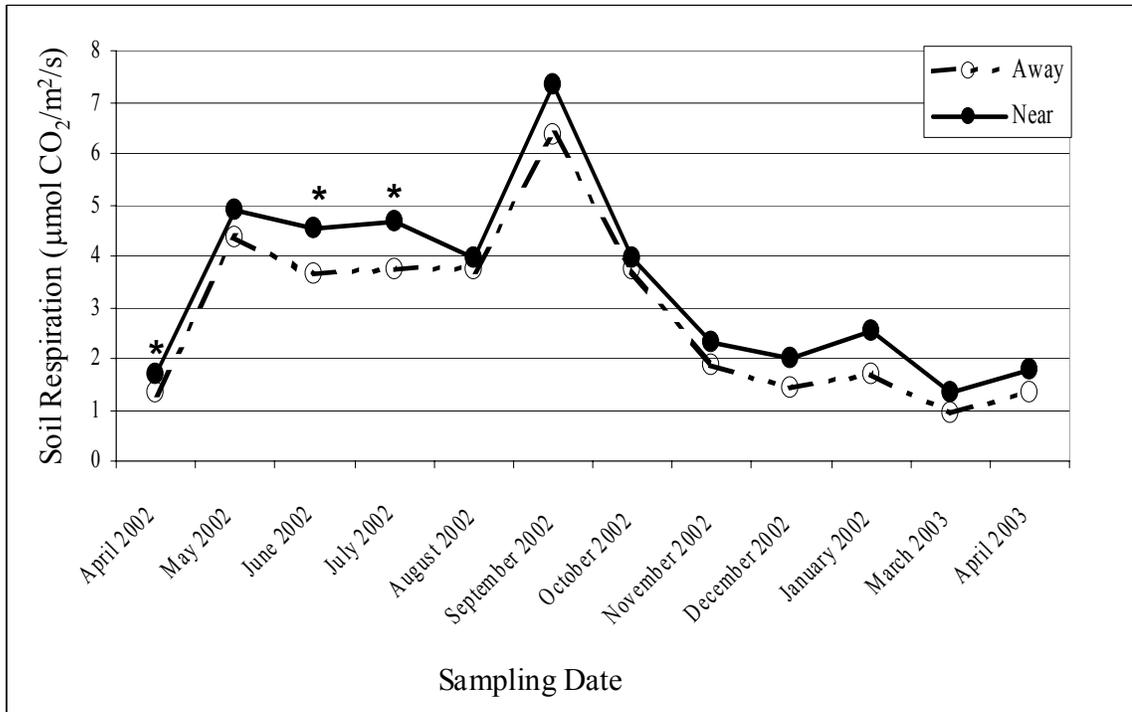


Figure 3.3. Effects of measurement position (near = adjacent to stump, away = 1.5 meters from stump) on soil respiration in thinned and unthinned loblolly pine plantations on the piedmont of Virginia, sampled over the course of one year following thinning. An asterisk denotes a significant difference between near and away measurements ($p < 0.10$).

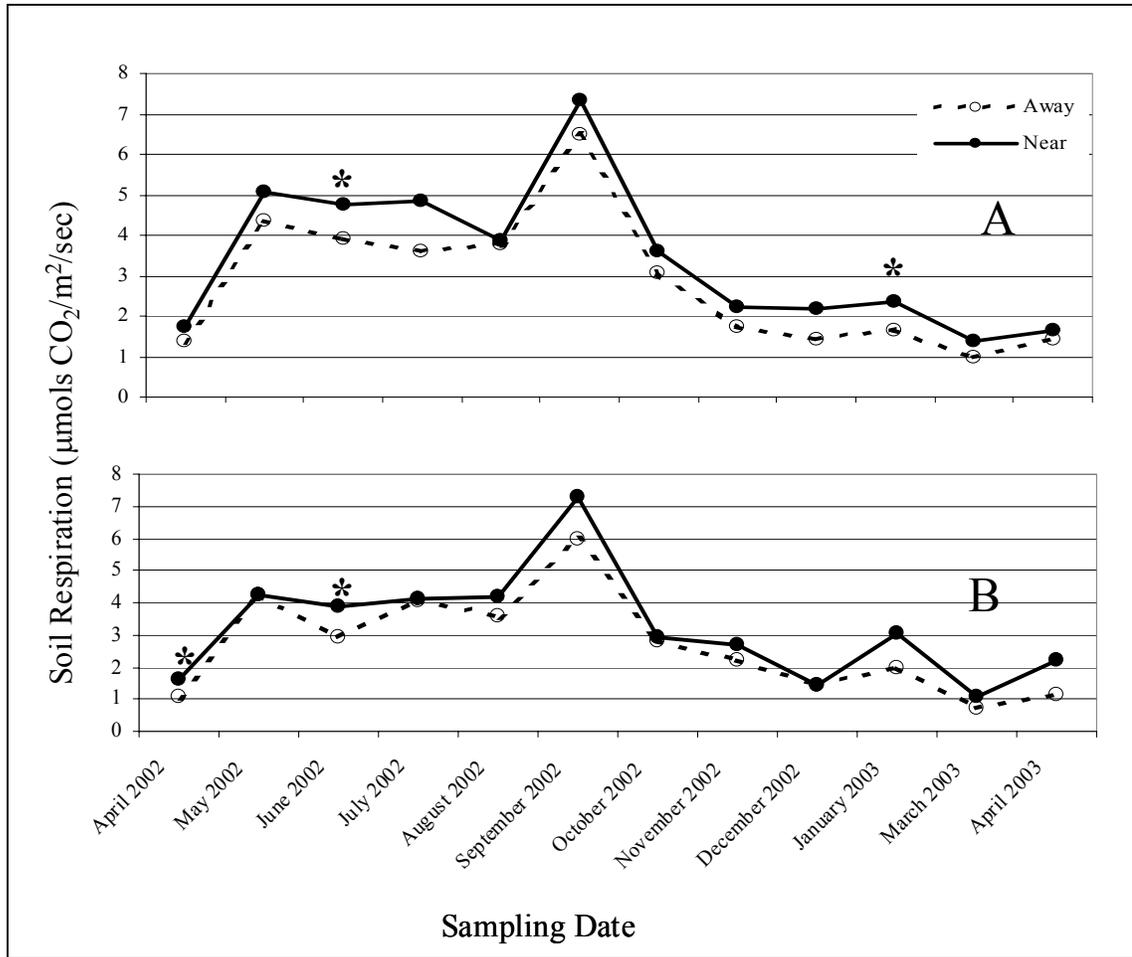


Figure 3.4. Effects of measurement position (near = adjacent to stump, away = 1.5 meters from stump) on soil respiration in thinned (A) and unthinned (B) loblolly pine plantations on the piedmont of Virginia, sampled over the course of one year. An asterisk denotes a significant difference between near and away measurements ($p < 0.10$).

Effect of treatment on soil temperature and moisture

Soil temperatures in thinned stands ranged from an average low of 4.3 degrees C in January to a high of 23.5 degrees C in August. In unthinned stands temperature ranged from an average of 5.0 degrees C in January to 21.7 degrees C in August. Temperature was significantly different between the thinned and unthinned stands for ten of the twelve sampling dates (Fig. 3.6). Temperature was significantly higher in the thinned stands from May to October and significantly lower from November to March (Fig. 3.6).

In thinned stands mean volumetric soil moistures ranged from a high of 12.2% in August to a low of 31.4% in April. Unthinned stands ranged from 7.5% in June to 26.3% in October. While soil moisture was consistently higher in thinned stands over the entire year, it was only significantly higher in thinned stands on six sampling dates (Fig. 3.7).

Use of regression for soil respiration predictions

In order to better understand the affects of thinning on E_c across various temperature ranges throughout the course of the year, two separate models were constructed using linear regression. The first model was created to examine the relationship between thinning and E_c , and the second was created to help explain E_c variations within the thinned stands.

Predicted effects of treatment on respiration

The first model utilized 1151 observations over the twelve-month sampling period (Fig. 3.8). The model was developed using treatment, soil temperature, soil moisture, two transformations of temperature, a treatment*²temperature interaction, a moisture*treatment interaction, a moisture*temperature interaction, and a position*temperature interaction. This model explained 41.6% of the E_c variation across the one-year study. The most significant variable in the model is temperature explaining 29.3 % of the variation. The natural log and square of temperature collectively explain 3.4 % percent of the variation. Treatment had a significant but small influence on E_c , less than one percent of the variation combined in the form of a monomial and polynomial in the treatment x square temperature and treatment x moisture interactions (Table 3.1).

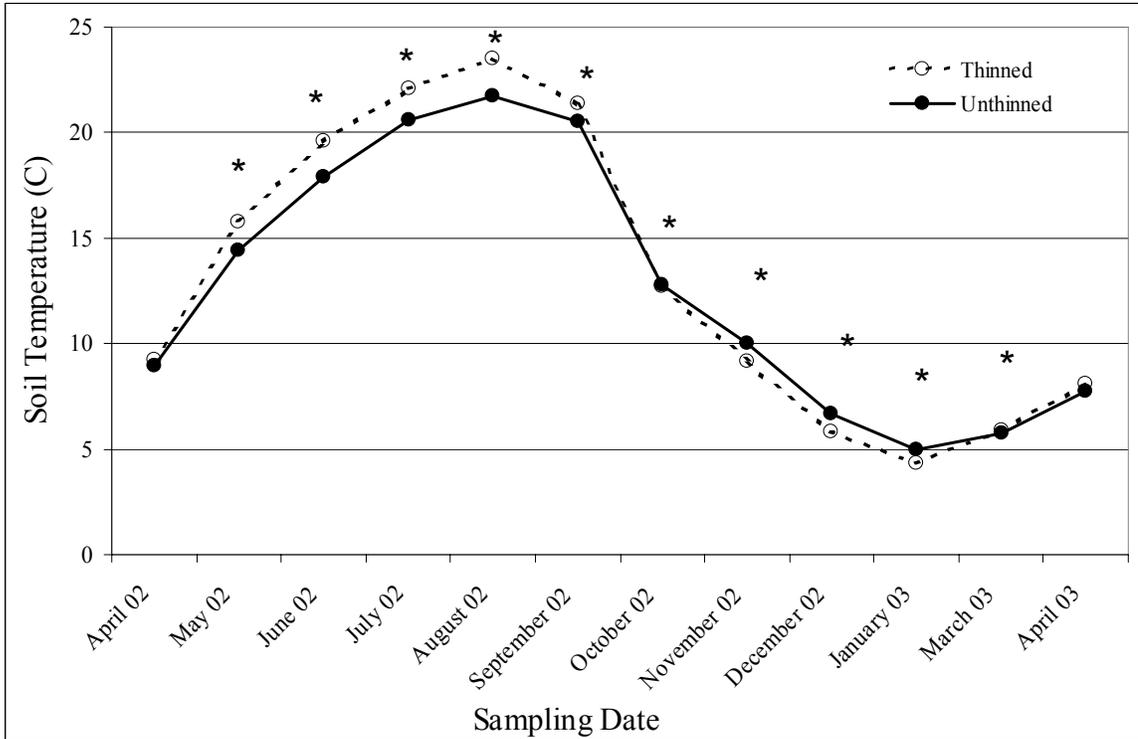


Figure 3.5. Soil temperature as affected by the thinning of a 22-year-old loblolly pine plantation on the piedmont of Virginia, over the course of one year following thinning. An asterisk denotes a significant difference between thinned and unthinned stands ($p < 0.10$).

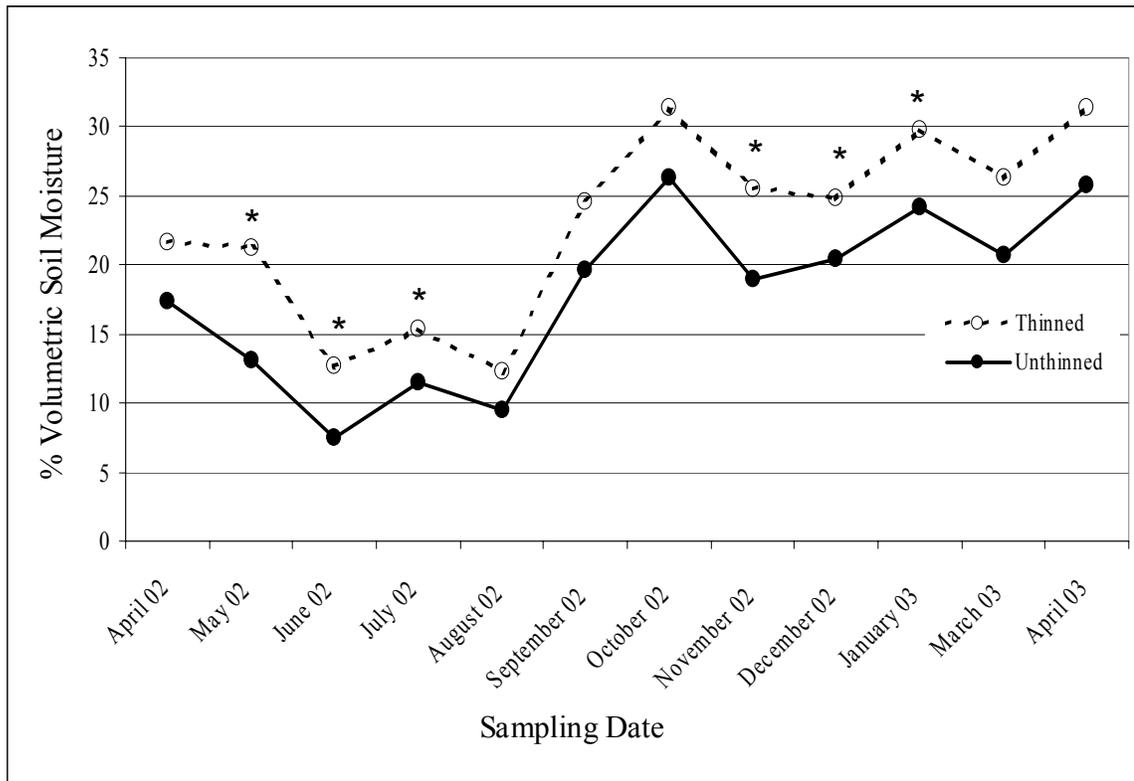


Figure 3.6. Volumetric soil moisture as affected by the thinning of a 22-year-old loblolly pine plantation on the piedmont of Virginia, sampled over the course of one year following thinning. An asterisk denotes significant differences between thinned and unthinned stands ($p < 0.10$).

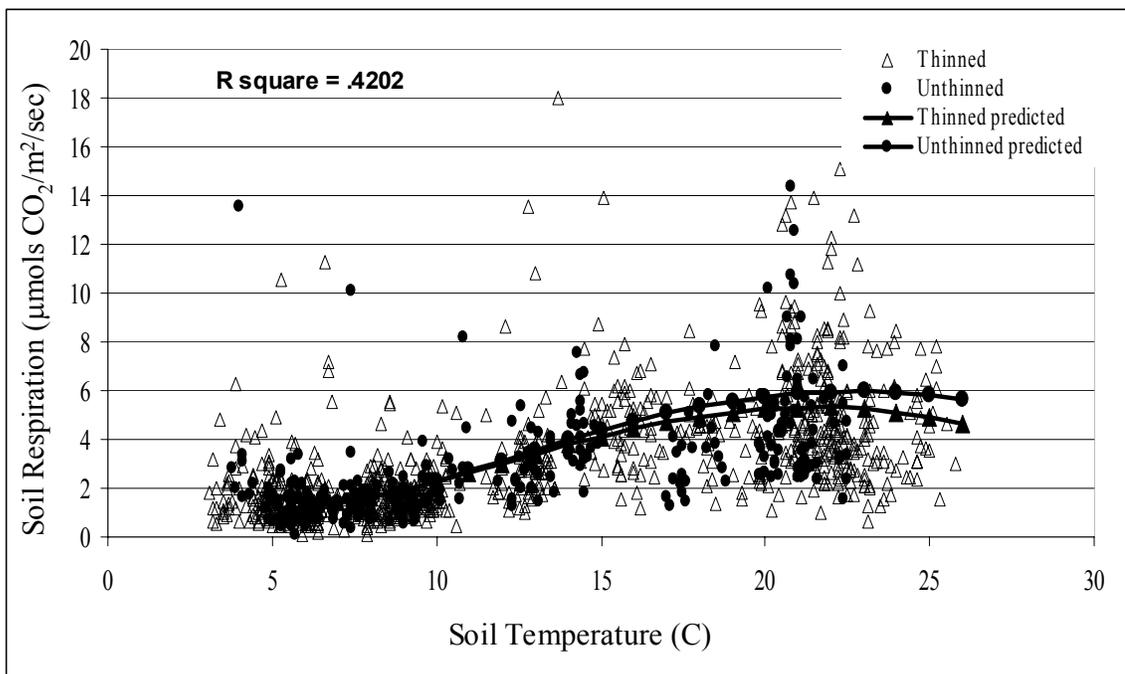


Figure 3.7. Predicted soil respiration across a range of temperatures, one year following the thinning of a 22-year-old loblolly pine plantation on the piedmont of Virginia (1151 total observations).

Table 3.1. Parameters influencing soil CO₂ efflux rates between 22-year-old thinned and unthinned loblolly pine stands on the piedmont of Virginia over a 12 month period (1151 total observations).

| Parameter | Soil CO ₂ Efflux (μmol/m ² /sec) | | | |
|------------------------------------|--|------------------------|-----------------------------|--------|
| | Parameter Estimates | Partial R ² | t Value | Pr> t |
| Soil Temperature | 2.38081 | 0.2928 | 8.78 | <.0001 |
| Soil Moisture | -0.03739 | 0.0534 | -2.15 | 0.0318 |
| Soil Temperature Squared | -0.04407 | 0.0331 | -7.81 | <.0001 |
| Position*Soil Temperature | 0.02334 | 0.02 | 6.27 | <.0001 |
| Soil Moisture*Soil Temperature | 0.00636 | 0.012 | 5.42 | <.0001 |
| Treatment*Soil Moisture | -0.03185 | 0.0062 | -3.74 | 0.0002 |
| Natural Log Soil Temperature | -12.58796 | 0.001 | -8.76 | <.0001 |
| Treatment | 0.76532 | 0.0009 | 3.32 | 0.0009 |
| Treatment*Soil Temperature Squared | -0.000805 | 0.0008 | -1.81 | 0.0699 |
| Model | Intercept = 11.27157 | | Total R ² =.4202 | |
| | Pr>F=<.0001 | | | |

Predicted effects stumps and trees on soil respiration

The second model used 863 observations to create separate models for new stumps, old stumps and trees within thinned stands, and compared the three models to one another. This model was developed using measurement location, soil temperature, soil moisture, two transformations of soil temperature, position*natural log temperature, and temperature*moisture as the explanatory variables. This model explained 43.3% of the variation in E_c within the thinned stands.

The separate models for each measurement location were not significantly different from one another. The model explained 39.3 % of the variation in E_c for new stumps, 46.6% of the variation for old stumps, and 44.7% of the variation for trees within the thinned stand. Temperature was the most significant variable in the model explaining 26.3% of the variation for new stumps, 26.2% for old stumps, and 33.9% for trees located within the unthinned stand.

DISCUSSION

Effects of treatment on temperature and moisture

Soil temperature was clearly influenced by the thinning of loblolly pine plantations. The thinning of the stands resulted in a significant difference in soil temperature for 10 out of the 12 sampling dates. Soil temperatures within the thinned stands were more heavily influenced by season, when compared to unthinned stands, making the extremes of seasonal temperatures more evident. This is in agreement with Della-Bianca & Dils (1960), and Nowak et al. (1991) who saw temperature increases in thinned stands during spring and summer months, and decreases in autumn and winter.

These dramatic temperature fluctuations may be explained by a variety of reasons. Most obviously the loss of canopy cover makes the forest soil more susceptible to changes in ambient temperatures, increasing convection between stand and atmospheric temperatures. Also, temporary reductions in litterfall, as documented by Vesterdal et al. (1995) in Norway spruce stands, reduce the amount of overall insulation provided to the soil by the forest litter layer. Skidder disturbance also furthered this through the removal of the protective litter layer, exposing bare soil to direct sunlight and ambient temperatures.

Coupled with extreme temperature fluctuations in thinned stands was increased volumetric soil moisture. Moisture was consistently higher in thinned stands, but only significantly higher from May to July and from November to January. These increases in soil moisture following thinning were also seen by Della-Bianca & Dils (1960) who noted differences following the thinning of red pine plantations. As a whole, these increases of soil moisture in thinned stands are likely explained by reduced transpiration rates. The reduction of canopy cover and live root systems greatly inhibits the uptake of soil solution by the stand. The effect is most drastically expressed in the early growing season, May to July, when soil moisture was significantly higher. Later in the growing season from August to October, increased temperatures and direct sunlight in the thinned stand may have enhanced evaporation to levels greater than those of unthinned stands. This increased evaporation in thinned stands will likely make the effect of treatment on soil moisture negligible by counter balancing the higher transpiration rates in unthinned stands. Later in the year, November to January, transpiration and evaporation rates are

lower in thinned and unthinned stands. However, rain events in the fall and early winter may let thicker litter layers in unthinned stands hold more moisture. Reduced litter layers in thinned stands allow precipitation to more easily percolate into the soil, increasing soil moisture.

Effects of treatment on respiration

Reviewing the treatment ANOVA's, thinned stands appear to maintain slightly increased E_c on 8 sampling dates, with three of those dates being significant. However, when modeled using regression with temperature, moisture and position as explanatory variables, the relationship reverses, showing treatment having a significant affect with increased respiration in unthinned stands.

These apparent differences can be explained by temperature's effect on E_c . As stated earlier, when temperature was used as a covariate in the treatment ANOVA, all significant differences were negated. Because temperature is a main driver of E_c (Trumbore et al., 1996) and temperature was significantly different between the two treatments it was necessary to normalize temperature between the two treatments to look at the affects of treatment alone. Using regression, we were able to normalize temperature and moisture between thinned and unthinned stands and simply look at treatment's affect on respiration. This analysis showed that the thinning of loblolly pine stands slightly but significantly decreased E_c rates.

These findings are in agreement with Popescu (2001) who found reduced respiration rates following the harvest of trees in a clearcut loblolly pine stand on the piedmont of Virginia and Striegl & Wickland (1998) who observed the same following the harvest of jack pine stands. These studies showed that following a clear cut E_c was more than halved during the growing season. While thinning only resulted in the harvest of half of the trees in the stand, one may conclude that the loss of half of the root systems should explain more than the 3.4% of the variation explained in the regression model. However, there are several possible reasons why thinning did not have a large affect on E_c .

This slight reduction in respiration may be explained by a variety of physiological factors taking place belowground. While autotrophic respiration was likely halved, if no

root grafting occurred in the stand, there was likely an increase in microbial respiration. The newly killed root systems were exposed to high moisture contents and warm temperatures during the growing season. As noted by Hornsby et al. (1995), these conditions are known to greatly increase decomposition rates and therefore increase microbial respiration, closing the gap in respiration rates between thinned and unthinned stands.

Another explanation of only a small reduction in respiration rates following thinning is the likely increased root growth of remaining trees. As previously mentioned, Santantonio & Santantonio (1987) and Van Lear et al. (2000) found that thinning may enhance root growth of remaining trees given that there is less belowground competition for water and nutrients, as well as providing old rooting channels which facilitate new root growth. Increased soil temperatures and soil moisture during the growing season, may also help increase root development of surviving trees. Several papers have already noted that thinning will increase aboveground growth (Della-Bianca & Dils, 1960; Piennaar et al., 1985; Ginn et al., 1991; Peterson et al., 1997; Hasenauer et al., 1997) and photosynthetic rates (Ginn et al., 1991; Peterson et al., 1997; Gravatt et al., 1997; Zhenmin et al., 1999), and it is well noted that above and belowground processes are well correlated (Mou et al., 1995). This increased root growth in thinned stands will most certainly increase autotrophic respiration, helping to bridge the gap between rates in thinned and unthinned stands.

Effects of stumps and trees on respiration within thinned stands

It is interesting that there was no consistent pattern found between measurement locations within the thinned stands. This may infer that root systems from harvested and remaining trees were evenly distributed throughout the stand. By twenty two years of age, it is plausible that the roots systems had become quite expansive, easily spanning distances between new stumps, old stumps and remaining trees. Mou et al. (1995) observed some overlap of loblolly pine root systems in the upper soil layers by age three when planted at a density of 4 trees per square meter. Santantonio & Santantonio (1987) observed some root grafts following the thinning of 12 year old radiata pine, again indicating that root overlap had occurred.

Effects of measurement position on respiration

Respiration measurements taken at the base of trees and stumps were consistently higher than those taken away from trees or stumps in both thinned and unthinned stands. Near positions had significantly higher E_c for three of the sampling dates when the two treatments were analyzed together. Separating thinned and unthinned stands showed that near positions exhibited significantly greater E_c on two sampling dates each. This spatial affect can also be seen in the models for types and treatments through position*temperature interactions. This interaction shows that position is most significant at higher temperatures. This spatial affect is similar to those noted by Pangle & Seiler (2002), Popescu (2001) and Wiseman (2001) whom all have attributed this phenomena to higher root distribution near the base of trees. When alive, these roots increase E_c through autotrophic respiration, and on older stumps the decomposition of these roots likely increase E_c through heterotrophic respiration. This was observed by Popescu (2001), who noted overall mean respiration rates of 3.513 $\mu\text{mol CO}_2/\text{m}^2/\text{sec}$ near harvested stumps as compared to 2.558 $\mu\text{mol CO}_2/\text{m}^2/\text{sec}$ away from the stumps.

Effects of temperature on respiration

Temperature proved to be the most important driver in E_c , collectively explaining 32.7% of the variance in the treatment model, and 26.2-33.9% of the variance for the various type models. Temperature has repeatedly been noted as exuding the most influence upon E_c (Kirschbaum, 1995; Trumbore et al., 1996; Boone et al., 1998; Schlesinger & Andrews, 2000; Pangle and Seiler, 2002).

CONCLUSIONS

The main objective of this study was to determine how the thinning of a 22-year old loblolly pine plantation on the piedmont of Virginia affected E_c over the course of one year following harvest. Due to increased growing season soil temperatures, thinning resulted in increased soil respiration rates for one year following harvest. When compared at equal temperatures, thinned stands actually maintained slight, but significantly lower soil respiration rates. Soil respiration in both thinned and unthinned

stands maintained the hypothesized position effects, with near position respiration rates being consistently higher in both stands.

This study also examined the variability of soil respiration within recently thinned stands. Linear regression explained that there were no significant differences between respiration rates measured at 14-year-old stumps, newly harvested stumps, and new trees. However, the hypothesized position effect was still present for all three-measurement locations within the thinned stands.

This study further illustrated the strong influence of temperature on soil respiration. Soil temperature explained a majority of the variability in soil respiration rates in all of the models.

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CONCLUSIONS

The two main objectives of this study were to determine the effects of thinning on temporal and spatial patterns of soil respiration, and determine the effects thinning has on stored soil carbon. Thinning of a 22-year-old loblolly pine plantation resulted in slightly increased soil respiration rates for one year following harvest. This however was due to elevated soil temperatures during the growing season in thinned stands. When compared at equal temperatures, thinned stands had slight, but significantly lower soil respiration rates. Soil respiration in both thinned and unthinned stands maintained the hypothesized position effects, with near position respiration rates being consistently higher in both stands.

This study also examined the variability of soil respiration within recently thinned stands. Linear regression explained that there were no significant differences between respiration rates measured at 14-year-old stumps, newly harvested stumps, and new trees. However, the hypothesized position effect was still present for all three-measurement locations within the thinned stands. This study further illustrated the strong influence of temperature on soil respiration. Soil temperature explained a majority of the variability in soil respiration rates in all of the models that were created.

Sampling soil carbon fourteen years after the thinning of an eight-year-old loblolly pine plantation revealed a 31.9% increase in mineral soil carbon to a depth of 30 cm. Using two different sampling techniques, it was shown that soil carbon was evenly distributed throughout thinned stands, and negatively correlated with soil depth.

Observed increases of soil carbon in thinned stands were counterbalanced by decreases in aboveground volume production. When soil and aboveground commercial carbon masses were combined, thinning resulted in a 10% loss in stored carbon. To truly determine the effects of thinning on carbon storage it will also be important to examine storage brought about by final product alterations caused by thinning, and carbon costs induced by intermediate operations.

Based on the results of this study, one may infer that the thinning of loblolly pine plantations on the piedmont of Virginia will store an additional 11 metric tons of carbon in the form of soil carbon. If the data is representative of the 125,000 hectares of thinned

loblolly pine plantations in the southeastern United States; thinning could be expected to store an additional 1.375 million metric tons of carbon in forest soils.

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APPENDIX

ANOVA Table for measurement location (thinned tree, new stump, old stump, unthinned tree) analysis

| Source | DF |
|--|-----------|
| Block (1,2,3) | 2 |
| Location (thinned tree, new stump, old stump, unthinned tree (4 subsamples each)) | 3 |
| Error I (Block x Location) | 6 |
| Position (near, away) | 1 |
| Error II (Block x Position) | 2 |
| Position x Location | 3 |
| Error III (Block x Location x Position) | 6 |
| Total | 23 |

ANOVA Table for treatment (thinned vs unthinned) analysis

| Source | DF |
|--|-----------|
| Block (1,2,3) | 2 |
| Treatment (thinned (12 subsamples), unthinned (4 subsamples)) | 1 |
| Error I (Block x Treatment) | 2 |
| Position (near, away) | 1 |
| Error II (Block x Position) | 2 |
| Position x Treatment | 1 |
| Error III (Block x Treatment x Position) | 2 |
| Total | 11 |

VITA

Marcus Selig was born in Ocean City, Maryland on September 23, 1979. He graduated from Stephen Decatur High School in 1997 and attended Virginia Polytechnic Institute and State University where he earned a B.S. degree in Forest Resource Management. Marcus continued his education at Virginia Tech, earning a M.S. degree in Forest Biology under Dr. John Seiler, in 2003. He currently resides in Lafayette, Indiana with his wife Kristin, and is working as a research associate for the Purdue University Forestry Department.