



## Impacts of intensive forestry on early rotation trends in site carbon pools in the southeastern US

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### Abstract

The effects of different silvicultural practices on site, especially soil, carbon (C) pools are still poorly known. We studied changes in site C pools during the first 5 years following harvesting and conversion of two extensively managed pine-hardwood stands to intensively managed loblolly pine plantations. One study site was located on the lower Atlantic Coastal Plain in North Carolina (NC) and another on the Gulf Coastal Plain in Louisiana (La). Four different harvesting-disturbance regimes were applied: stem only harvest (SO), whole tree harvest (WT), whole tree harvest with forest floor removal (WTFF), and full amelioration, i.e. whole tree harvest, disking, bedding and fertilization (FA; only in NC). Each harvesting-disturbance regime plot was split and one-half received annual herbicide treatments while the other half received no herbicide treatments.

In NC, soil C decreased slightly with WT, and increased with FA, otherwise no significant changes were detected. In La, there was a consistent decrease in soil C content from the pre-harvest value in all cases where herbicides were applied. All treatments caused a reduction in the forest floor C pool in NC. In La, the most intensive treatments also resulted in a decrease in the forest floor C, but to a smaller extent. In contrast, there was no net change in forest floor C with the SO and WT treatments, even though significant amounts of logging slash were added to the forest floor at harvest in the SO plots and not in the WT.

Herbicide treatment clearly decreased the C pool of hardwoods and understory, and more than doubled that of planted pines. Carbon accumulation in the planted pines was similar for trees growing in the SO, WT, and WTFF treatments on both the LA and NC sites. The full amelioration treatment (only applied at the NC site) led to a significant increase in C sequestration by the planted pine component. Due to a large amount of voluntary pines, total 5-year pine C pool was highest on the non-herbicide intensive management plots on the NC site, however.

The differing response patterns of soil and forest floor C pools between the two sites may be due to their differing drainage-summer rainfall regimes. Our results suggest that while poor drainage-wet summer conditions may be impeding carbon loss from the soil component it may be accelerating the rate of decomposition of the forest floor and slash on the soil surface.

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## 1. Introduction

Intensive plantation forestry is practiced by industry on 14.0 million hectares in the southeastern United States. On these lands intensive forest management and the use of genetically improved planting stock have led to more than a three-fold increase in productivity over natural forest production levels, and technologies to be implemented have the potential to double production again in the future (Farnum et al., 1983). However, to realize these higher levels of productivity will require more frequent harvest, more intense chemical and/or mechanical site preparation, artificial regeneration with genetically improved loblolly pine seedlings that will demand more site resources, intense herbaceous weed control, and fertilization on nutrient-deficient sites (e.g. Neary et al., 1990; Richter et al., 1994; Sword et al., 1998; Borders and Bailey, 2001). These intense forest management practices have both direct and indirect effects on processes affecting site productivity, and element cycling (e.g. Morris and Lowery, 1988; Henderson, 1995). Increased productivity will enhance carbon sequestration rates and carbon inputs to the forest floor and soil pools (Hepp and Brister, 1982) but management practices such as tillage and drainage may also increase carbon loss rates from the soil and forest floor (Pritchett, 1979); the net impacts are still largely unknown. Although research on the effect of intensive management on stand growth and yield, and ecosystem processes such as nutrient mineralization has been extensive, reports on intensive management effects on site C dynamics are still scanty. This is largely because C dynamics only recently became of major interest as part of the climate change problematics (e.g. Houghton et al., 1990).

Impacts of harvesting on carbon pools represented by standing vegetation prior to harvesting can be easily assessed by measuring changes in timber inventory. However, changes in soil carbon pools following harvesting and stand establishment are not easy to document. Harvesting and site preparation result in considerable carbon inputs to the forest floor, redistribution of organic matter across the site, and incorporation of organic matter to various depths within the upper part of the soil profile. The type of harvest performed may itself determine whether an increase

or decrease in soil carbon is observed after logging (Johnson, 1992; Johnson and Curtis, 2001).

In addition to logging impacts on carbon inputs and carbon distribution within a site, overstory removal and subsequent understory vegetation control alter the soil moisture, temperature and aeration regimes thus impacting the soil environment for organic matter decomposition (e.g. Edwards and Ross-Todd, 1983; Henderson, 1995). Changes in vegetation composition, and fertilization, may also alter litter and subsequently forest floor and soil organic matter quality (Polglase et al., 1992a–c). These alterations can be either positive or negative factors affecting microbial activity and decomposition depending on, e.g. soil physical characteristics and drainage (cf. Gholz et al., 1985; Wardle and Parkinson, 1990; Polglase et al., 1992b; Busse et al., 1996; Grierson et al., 1999). Thus, it is understandable that conflicting assessments of intensive forestry impacts on soil carbon pools exist.

Although the impacts of harvesting on soil C have been studied in some forest types (e.g. Johnson and Todd, 1997; Knoepp and Swank, 1997), there is still little information on how site C pools are affected by the intensive management practices applied in short rotation (15–20 years) pine plantation culture in the southeastern United States. The capacity of forest stands to enhance site C sequestration has been best documented in studies on de- and afforestation of erodible agricultural lands (Giddens and Garman, 1941; Giddens, 1957; Delcourt and Harris, 1980; Huntington, 1995; Richter et al., 1995; Van Lear et al., 1995). Most forest C accretion studies have been conducted on well-drained upland soils that were naturally regenerated to forest following agricultural abandonment. We still urgently need more information on the response patterns of C pools for the full range of site types being utilized for intensive plantation management, and for repeated harvest on these sites. This information would greatly improve modeling of forest C dynamics for one of the most intensively managed forest ecosystems in the world. The current model (Birdsey, 1996) being utilized for assessing the C dynamics of this ecosystem does not directly consider soil drainage and climate impacts on C dynamics. The objective of this paper is to summarize changes in pre-harvest carbon pools that have occurred during the first 5 years following a wide range of harvesting-disturbance treatments and conversion of lower Coastal

plain pine-hardwood stands to intensively managed loblolly pine (*Pinus taeda* L.) plantations.

## 2. Site description

The NC site is on the Croatan National Forest at approximately 76°48'W longitude and 34°55'N latitude. The La sites are on the Kisatchie National Forest at about 92°30'W longitude and between 30°0' and 31°45'N latitude.

The sites are located on the Coastal Plain, which is characterized by cool winters and hot, humid summers. The NC site receives an average of 136 cm of rainfall annually and the average temperature is 16 °C while the annual rainfall on the La sites is about 154 cm with an average temperature of 19 °C.

Prior to harvesting, the stands on both sites were comprised of approximately 55-year-old pine stands with a component of mixed species of hardwoods. The dominant pine species was loblolly with some longleaf pine (*Pinus palustris* Mill.) and shortleaf pine (*Pinus echinata* Mill.). Typical hardwood species in the pre-harvest tree stands included the following: oak (*Quercus* spp.), sweetgum (*Liquidambar styraciflua* L.), flowering dogwood (*Cornus florida* L.), red maple (*Acer rubrum* L.), yellow-poplar (*Liriodendron tulipifera* L.), American holly (*Ilex opaca* Ait.), sourwood (*Oxydendrum arboreum* L.), magnolia (*Magnolia* spp.), hickory (*Carya* spp.), and black cherry (*Prunus serotina* Ehrh).

The soils at the NC site are predominantly Goldsboro (fine-loamy, siliceous, subactive, thermic, Aquic Paleudults) (block 1) and Lynchburg (fine-loamy, siliceous, semiactive, thermic, Aeric Paleaquults) (blocks 2 and 3). The soils at the La site are Malbis (fine-loamy, siliceous, subactive, thermic Plinthic Paleudults) (block 1), Glenmora (fine-silty, siliceous, thermic Glossaquic Paleudalfs) (block 2), Metcaf (fine-silty, siliceous, semiactive, thermic Aquic Glosudalfs) (block 3), and Mayhew (fine-smectitic, thermic Chromic Dystraquerts) (block 4). Blocking was designed to capture the variation in soils.

## 3. Study design

Data from two sites belonging to the long term site productivity (LTSP) network (Powers et al., 1990)

were used in this analysis. One site is on the lower Atlantic Coastal Plains in North Carolina, and the second site is on the Gulf Coastal Plains in Louisiana.

The core LTSP study design is a series of nine treatments that stress two key factors related to site productivity commonly altered during harvest: organic matter removal and soil compaction. The (artificially induced) compaction aspect will not be addressed in this paper. We used data from the uncompacted treatments only, except for the additional “full amelioration” treatment in NC (described below).

The study is a 3 × 3 factorial, replicated on three blocks (NC) or four blocks (La), with three levels of organic matter removal: stem only (SO), whole tree (WT), and whole tree plus forest floor (WTFF). For the SO plots all logging slash was left on-site. For the WT treatment, all slash and foliage associated with the harvest trees was removed. The WTFF received the same logging treatment but an additional disturbance treatment was applied by removing all of the litter and humus layers by hand raking. In addition to the core treatments, an amelioration treatment referred to as “full amelioration” (FA) was included at the NC site on each block. Plots that had received WT removal and moderate compaction were disked, bedded, and fertilized with 225 kg ha<sup>-1</sup> of triple super phosphate before planting. This treatment represents the accepted site preparation practice for establishing loblolly pine on the soil types present on the NC installation.

Each treatment was imposed on a 0.42 ha plot, which was split in half. One split-plot received complete weed control while vegetation on the other split-plot was allowed to grow freely with the pine. Weed control treatments were applied annually until crown closure. Competing vegetation was eliminated by using repeated chemical application (Accord, Arsenal, and Oust) in combination with mechanical removal. Volunteer pines were treated as competing vegetation and thus were controlled in both the herbicided and non-herbicided plots at the La site, and in the herbicided plots but not in the non-herbicided plots at the NC site. The NC site was double planted with loblolly pine on a 3 m × 3 m spacing with the second tree removed after 1 year. In La, containerized seedlings were planted at 2.5 m × 2.5 m spacing.

In La, block 1 was planted in February 1990, block 2 in February 1992 and blocks 3 and 4 in February

1993. All three of the NC blocks were installed in April of 1992. In each case, harvesting was completed in the summer before planting. While the La blocks were planted in different years, the climatic variations were small enough that pine growth did not show differences that would have hindered our analyses (A. Tiarks, personal observation).

#### 4. Methods

All measurements were first conducted in the pre-harvest stand, and repeated 5 years after the treatments.

Soil samples were collected with a hammer-driven 6.3 cm × 30 cm soil sampler and each soil core was divided into three equal sections corresponding to the 0–10, 10–20, and 20–30 cm depths. In NC samples were collected from three sample points on each plot, while in La, 10 samples were collected per plot. Samples were collected at random locations within the plots. All soil samples were dried, passed through a 2 mm sieve, and weighed. The samples were composited across all depths and then by plots. Subsamples of the composites were analyzed for total C by dry combustion with infrared absorption detection (NA 1500 Carlo-Erba C/N/S analyzer in NC, and Leco 2000 CNS analyzer in La). On the bedded FA plots, two sets of post-treatment samples were taken: in beds and between beds. The proportion of area covered by beds was estimated to be two-thirds, and the average

soil pools across the plots were calculated accordingly. For the La site, only the 0–10 cm layer samples were available for the pre-harvest C analysis.

Three types of biomass sampling (tree stand, understory, and forest floor) were used to quantify the organic matter dry weights and nutrient concentrations of all above ground components. The details on the biomass sampling are available in internal reports at the USFS RTP and Pineville research stations.

The pre-harvest tree stand, planted pines on the whole area of the post-harvest measurement plots, and voluntary pines plus hardwoods on three 3 m × 3 m subplots per plot, were inventoried for species, diameter at breast height (DBH) and/or root collar diameter (RCD).

In NC, biomass and C concentration by tissue type were determined for 36 pre-harvest pines (12 of each three pine species), 41 pre-harvest hardwoods (3–9 per species), 34 planted plus 30 voluntary loblolly pines after 5 years, and 226 hardwoods (10–30 per species) after 4 years. For pre-harvest pines and all post-treatment stand species, equations relating total above-ground biomass and total aboveground C content to DBH or RCD were developed. A non-linear model

$$y = p1 \cdot D^{p2} \quad (1)$$

where  $y$  is the biomass C content,  $p1$  and  $p2$  are the parameters estimated from the data, and  $D$  = DBH or RCD was used (Fig. 1). This procedure produced unbiased estimates, with coefficients of determination

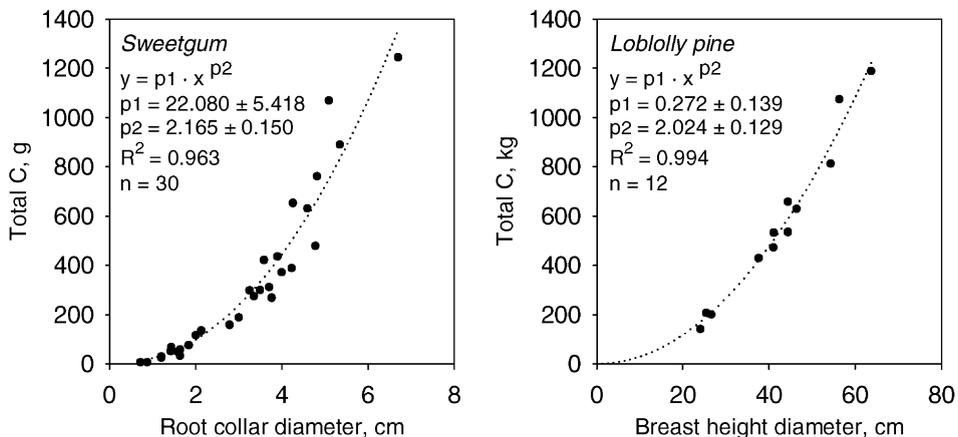


Fig. 1. Examples of the equations used to estimate tree-level carbon contents: post-treatment sweetgum C and pre-harvest loblolly pine C content vs. diameter.

between 0.900 and 0.990. These equations were then applied to the tree inventory data to obtain per area unit values for the whole stands. For pre-treatment hardwoods, equations relating component biomass to diameter as

$$y = p_1(\text{DBH}^2)^{p_2} \quad (2)$$

were developed, and C contents were obtained by multiplying the biomass values by component C concentrations.

In La, 27 pine trees per block were felled for measurements. A biomass prediction equation developed in the region (Baldwin, 1987) was used to predict the biomass of each tree. Biomass values were transformed into C assuming a 50% C concentration.

Understorey biomass was estimated using three 0.5 m radius clip-plots from each measurement plot in NC. All plants less than 2.54 cm in DBH were clipped at ground level and transported to the lab. Forest floor samples were collected at the same time as the clip-plot samples. Five 0.5 m<sup>2</sup> subplots were sampled for each measurement plot. Within these subplots, the forest floor was removed by hand down to the mineral soil and separated into a litter (L and F horizons) and a humus layer (H horizon). The samples were air-dried and the large woody debris was removed and weighed separately from the remainder of the forest floor. In La, five 1 m<sup>2</sup> samples were collected from each plot before harvest. The 5-year biomass samples were collected from four 1.25 m × 1.25 m subplots on each plot. The material was divided into woody material, grasses and forbes, and if possible, litter (mainly dead grass), plus new hardwoods in the 5-year sampling. There was no humus layer on the La site that could be sampled, which is typical of these sites. All samples were oven-dried, weighed and analyzed for nutrient concentration.

## 5. Statistical analyses

We used two approaches to analyze the changes in the C pools. Analysis of variance for split-plot designs was used to compare the effects of the different treatments. Changes in the studied variables during 5 years were used as independent variables for soil and forest floor C. End values were used as independent

variables for all plant biomass C pools. The basic variance model was of the form

$$y = \text{constant} + \text{block} + \text{OM} + \text{block} * \text{OM} + \text{H} + \text{H} * \text{OM} + \varepsilon \quad (3)$$

where OM denotes the level of the organic matter removal, H denotes herbicide treatment, and  $\varepsilon$  is the error term. The (insignificant) interactions block \* H and block \* H \* OM were included in the error term. The possible effect of the initial soil C content on the changes was further checked by including it in the analysis as a covariate. In this analysis, block \* OM was also included in the error term to increase the power of the analysis.

Additionally, paired comparison t test (dependent t-test) was used to compare the pre- and post-treatment values of the studied variables within treatments. This was done to check whether the changes induced by the individual treatments (organic matter removal—herbicide treatment combinations) differed significantly from zero.

Both sets of analyses were performed separately for the La and NC sites, as preliminary analyses showed that the treatment effects differed between sites. The analyses were done using SYSTAT software (SYSTAT, 1998).

## 6. Results

### 6.1. Soil

Few consistent changes in soil C from pre-harvest values were detected at the NC site (Fig. 2). Soil C decreased slightly but significantly with WT removal (*t*-test  $p = 0.028$ ; on average 80% of pre-harvest soil C remaining for WT with and without herbicides), and increased with the FA treatment ( $p = 0.053$ ; on average 244% of pre-harvest soil C remaining). On the La site (Fig. 2) there was a consistent decrease ( $p < 0.001$ ) in soil C content from the pre-harvest value in all cases where herbicides were applied (on average 76% remaining) but not on the non-herbicide plots.

On the NC site, the intensity of organic matter removal affected the soil C pool more than repeated annual herbicide treatment ( $p = 0.004$  versus  $p = 0.202$ , split-plot ANOVA for change in soil C), whereas the opposite was true on the La site ( $p = 0.316$  versus

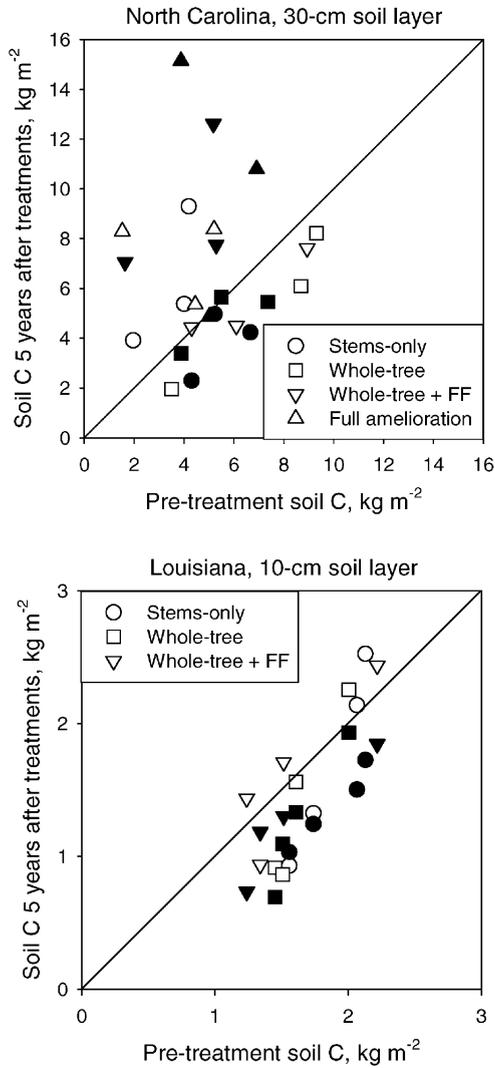


Fig. 2. Post-treatment vs. pre-harvest soil carbon pools of all individual sample plots: in a 0–10 cm soil layer for the Louisiana site, and 0–30 cm soil layer for the North Carolina site. The  $y = x$  diagonal indicates a situation where no change has taken place. Open symbols depict non-herbicided, and filled symbols herbicided plots.

$p = 0.028$  for organic matter removal and herbicide treatment, respectively). The intensity of organic matter removal did not alter the effect of herbiciding on soil C in La (interaction  $p = 0.641$ ), whereas in NC, herbicide treatment seemed to maintain high soil C pools on the two most intensive organic matter removal treatments (interaction  $p = 0.007$ ).

Five years after harvest, the soil C pool was clearly highest on the herbicided WTFF and FA plots on the

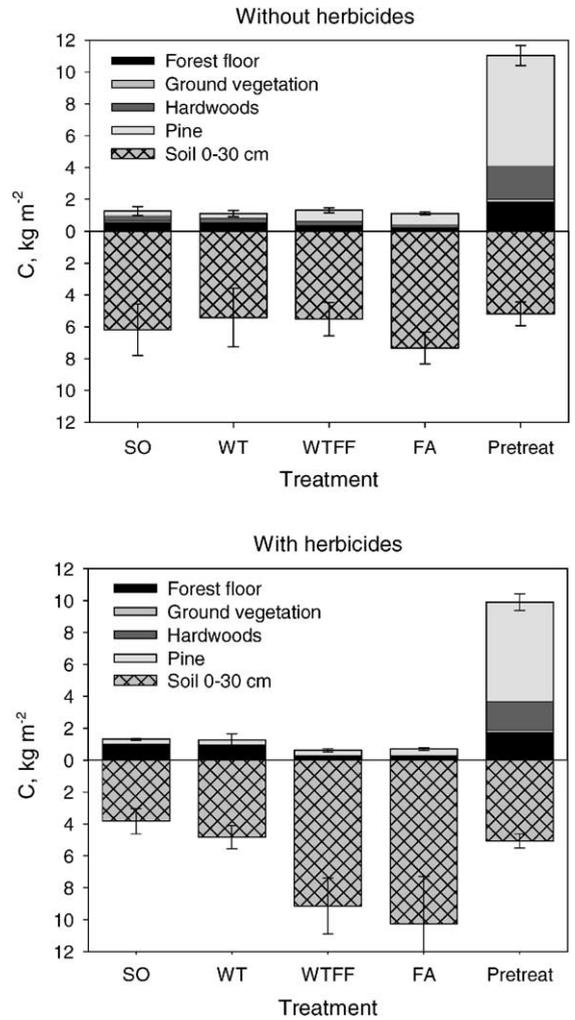


Fig. 3. Carbon pools 5 years after treatments, and in the pre-harvest stand, on the North Carolina site. Treatment means with standard error of mean vectors; above-ground SEM for the total C pool. SO: stems only harvesting, WT: whole tree harvesting, WTFF: WT plus forest floor removal, FA: full amelioration (see Section 3), pretreat: pre-harvest stand.

NC site (Fig. 3). On the La site, soil C pools were consistently higher on non-herbicided than herbicided plots (Fig. 4).

### 6.2. Forest floor

The average pre-harvest forest floor C pools at the NC and LA sites were 1.8 and 0.7  $\text{kg C m}^{-2}$ , respectively (Figs. 3 and 4). All treatments caused a reduction

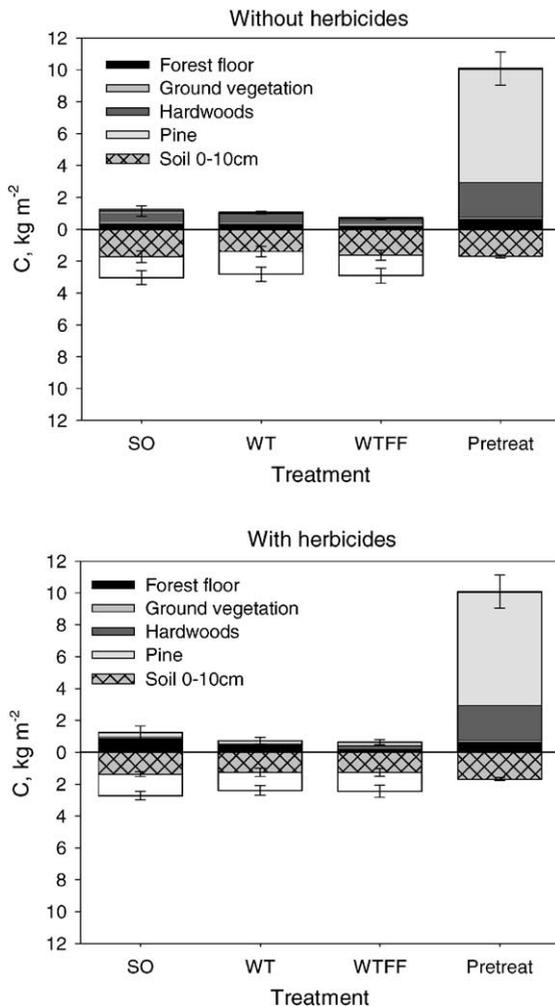


Fig. 4. Carbon pools 5 years after treatments, and in the pre-harvest stand, on the Louisiana site. Treatment means with standard error of mean vectors; above-ground SEM for the total C pool. Open boxes below 0–10 cm soil bars indicate the 0–30 cm layer that was analyzed only after treatments. See Fig. 2 for treatment abbreviations.

in this pool at the NC site ( $t$ -test  $p$ -values 0.011–0.062). When comparing the different treatments with split-plot ANOVA, herbicide treatment had a more significant effect on the change in forest floor C pool over 5 years than the level of organic matter removal ( $p = 0.031$  versus 0.056). The reduction in the forest floor C pool was on average smaller when herbicides were applied. The two most intensive removal levels caused the greatest reduction in forest

floor C (13–20% of the pre-harvest level remaining). The SO and WT treatments reduced the forest floor C pool to ca. 60 and 45%, respectively, of the pre-harvest level when herbicides were applied, and further to ca. 25% without herbicides.

At the La site, the WTFF also resulted in a decrease in the forest floor C ( $t$ -test  $p < 0.06$  both with and without herbicides), but to a smaller extent than on the NC site: ca. 45% of the pre-harvest level was present after 5 years. In great contrast to the NC site, there were no significant changes in forest floor C with the SO and WT treatments. When comparing the different treatments with split-plot ANOVA, neither herbicide treatment ( $p = 0.140$ ) nor the level of organic matter removal ( $p = 0.471$ ) proved to significantly affect the change in forest floor C pool.

### 6.3. Tree stand and ground vegetation

Before harvest, the pine biomass C pool was remarkably similar for the NC ( $6.4 \text{ kg m}^{-2}$ ) and the La site ( $7.0 \text{ kg m}^{-2}$ ) (Figs. 3 and 4). Five years after treatments, pine biomass C varied between 4.1% (WT without herbicides) and 10.0% (FA without herbicides) of pre-harvest values at the NC site, and from 0.9% (WT without herbicides) to 3.3% (SO with herbicides) at the La site.

The level of organic matter removal affected the pine biomass C pool significantly at the NC site ( $p < 0.001$  for planted,  $p = 0.042$  for volunteer pine,  $p = 0.009$  total, split-plot ANOVA for pine C pool 5 years after treatments; Fig. 5). At the La site, the level of organic matter removal did not have a significant effect ( $p = 0.210$ ), even though there was a trend toward more pine C having accumulated on the SO than on the WT or WTFF treatments. Herbicide treatment clearly increased the C accumulation to planted pines (Fig. 5). However, due to a large amount of voluntary pines, total pine C pool at year 5 was highest on the non-herbiced intensive management plots (WTFF and FA) at the NC site ( $p = 0.007$  for herbiciding,  $p = 0.042$  for herbicide \* OM-removal interaction; split-plot ANOVA). At the La site, herbicides increased the rate of pine C recovery at all levels of harvest-removal ( $p < 0.001$ ).

The hardwood C pools were of similar size, ca.  $2 \text{ kg m}^{-2}$ , on both sites prior to harvest (Figs. 3 and 4). The annual herbicide treatments reduced the hardwood

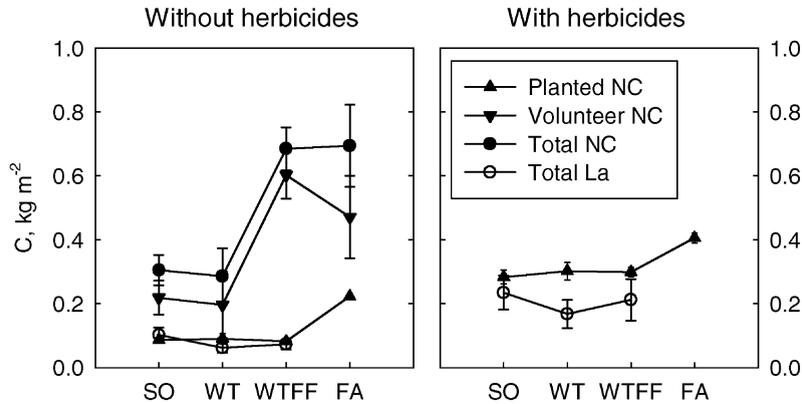


Fig. 5. Post-treatment pine biomass C pool after varying harvest-removal treatment on the North Carolina and Louisiana sites. Treatment means with standard error of mean vectors. For the NC site, planted and volunteer pines, and their sum, are shown separately. SO: stems only harvesting, WT: whole tree harvesting, WTFF: WT plus forest floor removal, FA: full amelioration (see Section 3).

C component to near zero at the NC location ( $p > 0.001$  for herbiciding in split-plot ANOVA). On the non-herbicided plots the proportion of hardwood C of the pre-harvest level varied, non-significantly, between 8 (FA) and 15% (SO). In La, the corresponding figures were 2.4 (WT) to 6.6% (SO) with herbicides, and 11 (WTFF) to 27% (SO) without herbicides ( $p = 0.001$  for herbiciding, 0.157 for organic matter removal in split-plot ANOVA).

Ground vegetation was a very small component of the total system C at both the NC and LA locations (Figs. 3 and 4). In the pre-harvest stands it represented less than one percent of the total system C pools. Five years after treatments, the ground vegetation C pool remained approximately at the pre-harvest level (non-herbicided plots) or was reduced to ca. half (herbicided plots) at the La site. In NC, herbicide treatments reduced the ground vegetation component to near zero. On the non-herbicided plots, the ground vegetation C pool was 60% of the pre-harvest level (SO) or clearly less.

## 7. Discussion

### 7.1. Changes in soil and forest floor C pools

Harvesting with methods that differed widely in the amount of harvest residue and forest floor left on site had few discernable effects on soil carbon pools

during the first 5 years on a site where this pool was originally relatively high (NC: on average 1.9–2.9% C in the 0–10 cm soil layer before harvest). Only with whole tree harvesting without site preparation was there a decreasing trend in soil C. On a site with a lower pre-harvest soil C pool (La: 1.0–1.4% C), there was a decreasing trend where herbicides were applied; with non-herbicided treatments, no change was detected. The elevated levels of soil C after the most intensive treatments (WTFF and FA, including herbicide treatment) were not expected. In the WTFF plots some of the forest floor C may have been incorporated into the mineral fraction during the forest floor removal process. The entire forest floor would likely have been incorporated into the soil on the FA plot. Technically, the increase in the soil C pool with the intensive treatments was due to an increase in the C concentration, as soil bulk density was lower 5 years after treatments than in the pre-harvest stand (post-treatment bulk densities did not differ significantly among treatments; data not shown). Soil C following clear-cutting and intensive site preparation is assumed to decrease by 20% over a 10-year period in current assessment modeling (Birdsey, 1996). In contrast to this assumption, clear-cutting followed by intensive site preparation in NC has actually shown an increase in soil C. Similarly, McClurkin et al. (1987) observed the organic matter content in the 0–5 cm mineral soil layer to increase from 4.8 to 6.6% over a 3-year period following clear-cutting of a 20-year-old loblolly pine

plantation. They attributed this increase in soil C to a rapid break-down of the forest floor and incorporation into the mineral soil fraction. In our La site, however, the use of herbicides that controlled most grasses, weeds and hardwoods, has resulted in a decline in soil C.

The response patterns of soil C pools differed considerably between the two sites. One possible explanation for this may be the differences that exist in moisture and temperature regimes for the two sites. The winter season is cool and wet at both locations. However, the growing season (March–October) at each site is quite varied. Growing season cumulative rainfall and associated average air temperature monitored on the two sites over the 5-year study period were 88.3 cm rain and 20.8 °C air temperature at the NC site versus 51.4 cm rain and 21.9 °C air temperature for the La site. Soils on both sites range from moderately to poorly drained (Tiarks et al., 1995, 1999). Poor aeration is likely to be a factor that limits decomposition rates on these sites during wet periods (Birdgham et al., 1991). In such a case, reduced evapotranspiration due to control of the ground vegetation with herbicides (Morris and Lowery, 1988) might be expected to keep decomposition rates low. Extended wet soil periods would be much more prevalent at the NC site than at the La site due to the differences in their rainfall distribution patterns (Tiarks et al., 1995, 1999). In addition, the warmer temperatures in La would also promote faster decomposition in the soil component. On another Atlantic Coastal site that has similar rainfall distribution to our NC site, Gresham (2002) reported that soil organic matter, 10 years after harvesting and re-establishment of a second rotation loblolly pine forest, had actually increased on a poorly drained soil and had not changed on a somewhat poorly drained soil. This study and ours both suggest that soil drainage and summer rainfall patterns do interact to determine decomposition rates of soil organic matter.

Soil C may decrease in subsequent years on the sites we studied due to the observed decrease in forest floor C pool, especially on the more intensively managed plots in NC. However, the expected reduction in C flux from the forest floor pool may to some extent be compensated for by higher fine root and aboveground litter production on these plots due to improved stand production (cf. Laiho and Finér, 1996; Laiho and

Laine, 1996). In most studies where a decline in soil C was found, the decrease took place during the first 5 years or so (e.g. Smethurst and Nambiar, 1990; Turner and Lambert, 2000), the period that was covered in our study. Gholz and Fisher (1982) found that in slash pine (*Pinus elliottii* Engelm.) plantations, soil C pools that initially decreased had returned to pre-harvest levels by age 5. Our study sites will continue to be monitored to define the soil C pool dynamics for the whole rotation.

The contrasting response in forest floor C observed at the two sites is interesting. On the NC site the forest floor and slash appear to decrease rapidly after harvesting, while on the La site the forest floor showed smaller reductions, and even increased in some cases. The mean annual water deficit is about 0 in NC and 80 mm in La (all the deficit occurs during summer). The La soils go through complete wet-dry cycles while the NC soils stay moist most of the year. Our results suggest that while poor drainage-wet summer combinations may be impeding carbon loss from the soil component it may be accelerating the rate of decomposition of the forest floor and slash on the soil surface. If this is true, it suggests that slash, coarse woody debris and the forest floor may play a more active role in carbon and nutrient cycling following harvesting on poorly drained-wet summer sites than on better drained-drier summer sites. Decomposition rates on the La site of twigs placed on the soil surface has been reported to be about one-half those observed on the NC site (Tiarks et al., 1999). The findings of Barber and Van Lear (1984) and Erickson et al. (1985) also lend support that dry-season moisture content may be determining the decay rate of logging residues. These results emphasize the importance of developing a better understanding of how soil drainage, rainfall and temperature regimes interact to affect forest floor dynamics.

The trend of a lesser forest floor in the non-herbicide plots is probably due to lower production of litter. Trees grown on the non-herbicide plots have to compete with the understory for resources (water and nutrients) from the soil, thus they tend to be smaller and have less leaf area and consequently less litter production than trees on the herbicide plots. The mean crown diameters in the herbicide plots were clearly larger than in the no herbicide plots (F. Sanchez, unpublished data).

The extent that the forest floor decomposes and mineralizes will be important in today's intensive forestry operations. It is likely that plantations being established today will achieve similar above ground tree biomass in a 20–25-year rotation to what was achieved in 50 years by the pre-harvest stands. Gholz and Fisher (1982) reported that by age 25 slash pine plantations contained about  $8 \text{ kg C m}^{-2}$ . Plantations established today with genetically improved stock and provided with competition control would be expected to far exceed these reported production rates (Buford and Stokes, 2000). Finding avenues for retaining the forest floor on-site during harvesting and getting this pool of nutrients cycling within the system represents a good opportunity to reduce or delay nutrient inputs that may be needed to support future intensively managed forest. If slash were left on site and at least partly incorporated into the soil, preferably after chipping, soil C pools might in general be increased which could improve productivity in the long term (e.g. Saloniemi, 1983; Barber and Van Lear, 1984; Pye and Vitousek, 1985; Sanchez et al., 2000). Although large accumulations of nutrient-poor organic matter may reduce site productivity (Kimmins, 1996; Murty et al., 1996), logging slash is not likely to pose such a problem (Fahey et al., 1991; Hyvönen et al., 2000; Buford and Stokes, 2000).

### 7.2. Tree stand and ground vegetation

Increased level of carbon and nutrient removal (WTFF and FA) did not result in reduced early pine growth on the NC site that was high in soil C (Table 1). The plots that had not received herbicide treatment at the NC site actually had three times more pine biomass in the WTFF and the FA treatments than in the SO or WT treatments. This was not because of faster growth of the planted pine, however, but because of a large component of pines that seeded into the harvest treatments that resulted in high surface soil disturbance, providing a favorable seed bed. Planted pines on the NC site were accumulating significantly more C in the FA plots than in any of the other treatments. At the La site, which had lower levels of pre-harvest soil C than the NC soil, there did appear to be a slight decrease in pine-C accumulation rate as the level of harvest-removal was increased above the SO level. This was true if herbicides were applied or not. These

Table 1

Average loblolly pine height (m) 5 years after treatments (standard deviation in parentheses)

Treatment	NC planted <sup>a</sup>	NC volunteer <sup>a</sup>	La <sup>b</sup>
SO <sup>c</sup>	3.39 (0.91)	1.97 (0.75)	3.96 (0.45)
SO + H <sup>d</sup>	5.39 (1.07)		4.62 (0.53)
WT <sup>e</sup>	3.81 (0.79)	2.25 (0.81)	3.45 (0.64)
WT + H	5.43 (1.25)		4.12 (1.10)
WTFF <sup>f</sup>	3.67 (0.80)	1.95 (0.67)	3.50 (0.83)
WTFF + H	4.74 (1.14)		4.43 (1.44)
FA <sup>g</sup>	5.92 (0.61)	2.65 (0.99)	
FA + H	6.28 (0.65)		

<sup>a</sup> North Carolina site.

<sup>b</sup> Louisiana site.

<sup>c</sup> Stems only harvest.

<sup>d</sup> Herbicide treatment (see Section 3).

<sup>e</sup> Whole tree harvest.

<sup>f</sup> WT + forest floor removal.

<sup>g</sup> Full amelioration (see Section 3).

results suggest that low soil C sites may be more sensitive to the level of organic matter removal or displacement in the logging process.

Controlling competition of hardwoods and ground vegetation improved the growth of the planted pine stand (Table 1, Fig. 5) as found in several other studies (e.g. Clason, 1984; Tuttle et al., 1985; Sword et al., 1998), but decreased the total above-ground plant biomass C pool. With repeated herbicide treatments, competing vegetation was reduced to almost zero on the NC site and to a minor component on the La site. Although improving the growth of the commercially important part of the stand at the early stages of development, complete control of competing vegetation may reduce the total plant C pool, but also cause changes in the soil organic matter quality on some sites that in the longer term reduce the positive effects of reduced competition (Polglase et al., 1992c; Busse et al., 1996; Sword et al., 1998). Due to differences in phenology, nutrient requirements and carbon allocation patterns of hardwoods versus pines, the reduction of the hardwood component would be expected to impact nutrient cycling and the input of carbon to the various C pools on these sites in the future (Wood et al., 1992). The herbicide treatments applied on these sites annually until crown closure would result in a much greater control of hardwoods than is achieved with typical hardwood release treatments used in intensive forest management, however. Industrial hardwood

release treatments are usually applied only once in a 20–30-year rotation.

Understory vegetation should peak in plantations at age 5 and then decline to constant level (Gholz and Fisher, 1982). Although the ground vegetation represents a small biomass component on these sites it may play an important role in maintaining nutrients in the early stage of development when crop tree demand is low and nutrient mineralization is high (e.g. Smethurst and Nambiar, 1989; Wood et al., 1992).

### 7.3. Problems in generalization

A problem in our study was the relatively low soil sampling intensity on the NC site (three samples per plot). According to Liski (1995), about 30 spatially independent samples were needed for 10% confidence in the mean soil C pool in a boreal pine stand; 8–10 was suggested after considering the relative change in confidence (see also Johnson et al., 1990). We know little of the extent of within-plot spatial variation in soil C on our sites. The coefficient of between-plot variation on the NC site before harvest varied from 20% (block 1) to 78% (block 3) for the 0–10 cm layer, and from 16 to 65% for the total pool in the 0–30 cm layer studied. If the within-plot variation were of the same order of magnitude as the variation in block 1, 20 soil samples would be needed to obtain 10% confidence for the mean soil C content in the 0–10 cm layer (0.05 risk level), and 10 samples for the total pool in the 0–30 cm layer. Our sampling procedures for other C pools, including forest floor (cf. Ilvesniemi, 1991) and soil on the La site, were more efficient. A pilot-study exploring the magnitude of the within-site variation in soil density was used to determine the number of samples in La. In spite of lower sampling intensity, variation about soil C treatment mean was only 22% on average in NC (range 14–34%), compared to 14% in La (range 9–16%). The mean soil C pool was higher in NC, which usually means higher variation as well. Thus, it seems that the low sampling intensity did not result in particularly poor confidence in this case.

The thickness of the soil profile studied for soil C changes after harvest was 30 cm in NC and only 10 cm in La. Changes in soil C may have occurred at greater depths in the profile (see Turner and Lambert, 2000). Future studies should assess soil C changes to a greater depth than was done at our two study locations.

### 7.4. Conclusions

Although the intensity of our soil sampling could have been better, it is obvious that no dramatic short-term soil C pool changes took place on our sites in the upper part of the soil profile after various harvesting and regeneration treatments were applied. The response of both the aboveground and soil C pools depended on the harvesting and site preparation methods. It also seems that the soil C pools may be positively affected by incorporating organic matter into the soil with site preparation. The level of organic matter removal had more influence on soil C pool than herbiciding in the NC site, while the opposite was true in La.

The variation observed in soil C pool response to different harvesting methods in different studies may be due to variation in site types, original soil condition, timing and realization of the operations, climatic factors, and/or interaction of some or all of these (see, e.g. Johnson, 1992). However, this study along with the meta-analysis (Johnson, 1992; Johnson and Curtis, 2001) suggests that a categorical assumption of soil C loss following harvesting is unwarranted. Further, our results suggest that while poor drainage-wet summer combinations may be impeding carbon loss from the soil component it may be accelerating the rate of decomposition of the forest floor and slash on the soil surface. Certainly, further study is still needed to identify sites that are especially susceptible to soil C losses, and management methods that are most likely to cause or prevent these losses. Productive sites with higher initial soil C pools (e.g. Liski and Westman, 1997) may be less sensitive than sites with low initial C pools. On the other hand, hydric soils may be more sensitive to changes in temperature and moisture regimes as a result of silvicultural practices (Trettin et al., 1995). Because the size of the organic matter pool in mineral soils represents the soil's potential to supply nitrogen, and in some cases much of its phosphorus supplying capacity, it is desirable to maintain organic matter when possible.

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