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Effects of Logging Residue Management on the Growth and Nutrient Distribution of a *Pinus taeda* Plantation in Central Louisiana, USA

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Abstract

A 37-year-old pine plantation was harvested. An experiment was established at the site with three levels of logging residue retention and two levels of weed control. By age 10 years retaining harvest residue increased pine volumes by 10 $m^3 ha^{-1}$ and weed control increased production by another 20 $m^3 ha^{-1}$. Growth differed between genetic family, but there was no genetic family x residue treatment interaction. Retention of logging residue without weed control increased the amount of carbon in the soil at age 5 years, but carbon levels decreased to pre-planting levels by age 10 years.

Introduction

In southern US, most of the original pine forest was cut and the land used for agriculture during the 19th and 20th centuries. These farms were abandoned because of declining crop yields, but periodic fires and lack of seed sources prevented re-establishment of forests. Low natural fertility and water holding capacity combined with farming-induced erosion and soil compaction meant that much of the area fits the criteria of degraded lands (Oldeman and Van Engelen 1993). Subsequent reforestation has restored some of the lost soil organic matter on many of the sites (Van Lear *et al.* 1995), but these coastal plain soils may again lose long-term productivity if forest management practices reduce the amount of organic matter and nutrients in the soil.

To monitor the effects of forest management on public lands, Powers *et al.* (1990) proposed a national study be initiated with treatments that manipulate the amount of logging residue retained, as well as soil compaction. Beginning with the prototype site reported here, more than 60 core installations and another 40 affiliated experiments have been established on both public and private lands in the US and Canada. Goals of the study include developing the scientific basis for sustaining productivity and validating practicable soil-based measures of

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sustainable productivity as encouraged by the international Montreal Process. Results from the first 5 years of replicated installations in Louisiana and Mississippi were reported in the 3rd CIFOR network workshop (Tiarks *et al.* 2000). In this paper, the effects of residue retention and weed control on pine growth and nutrient distributions in a 10-year-old plantation are presented.

Location and Site Description

The study site is on the USDA Forest Service's Palustris Experimental Forest in Rapides Parish, Louisiana approximately 50 km southwest of Alexandria. The site (latitude 31°02'N, longitude 92°38'W, altitude 45 m) is on rolling terrain formed from coastal plain sediments consisting of unconsolidated loams and clays. The soils are Malbis fine sandy loam (Kerr *et al.* 1980) belonging to the Plinthic Paleudults in the USDA Taxonomy classification. These soils are moderately well drained, acidic, and are low in organic matter, available P and exchangeable bases. A water table fluctuates about the 100 cm depth in the winter and spring, but is rarely present in the summer months (Tiarks *et al.* 1995). The soil water holding capacity available during the growing season is about 325 mm for the 2 m deep profile.

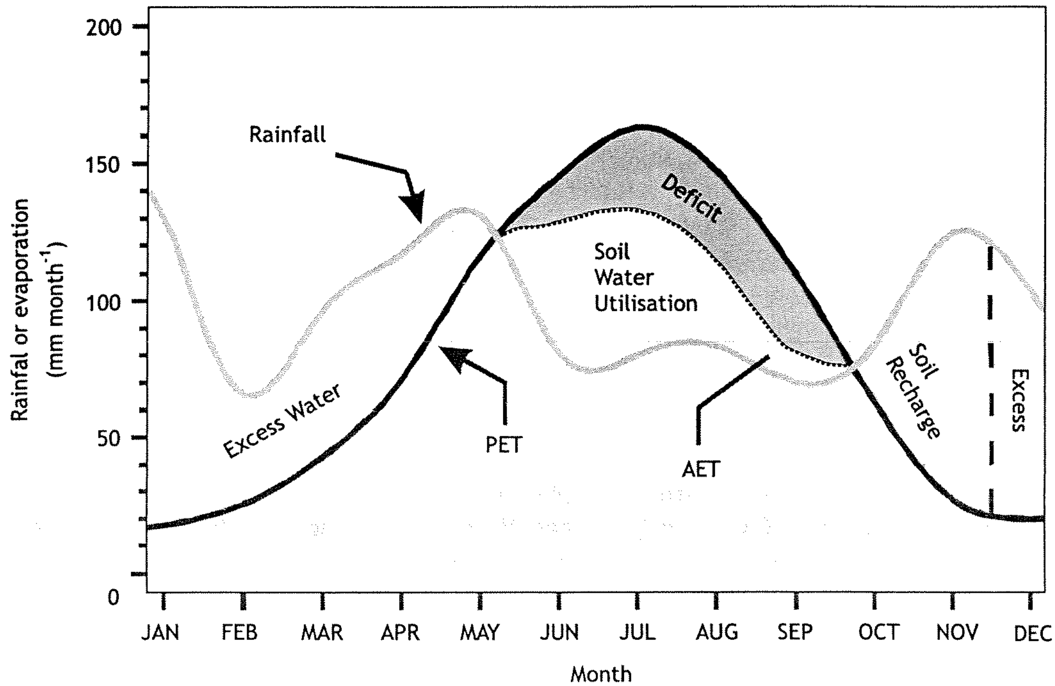
Native vegetation for the area was *Pinus palustris* Mill. forests which were removed in the early 1900s. As no attempt was made to reforest the area and/or control fire, the vegetation developed into an open stand of grass with a scattering of *Quercus marilandica* Muenchh. and *P. palustris* saplings. In 1953, the stand harvested for this study was established by disking strips into the grass and direct seeding. Two years after seeding, the stand consisted of 1032 seedlings ha^{-1}. The stand received management typical to the local area, which included several thinnings and winter prescribed burns about every 3 years, the last being 9 months before harvesting in October 1989. At harvest, the number of trees was 226 ha^{-1} and averaged 20.5 m in height and 30.3 cm dbh. Stem analysis was done on 27 trees selected to represent the diameter classes. Nonlinear regression was used to develop a height-age curve for the previous stand (Baldwin and Feduccia 1982).

The climate type is humid mesothermal without a dry season according to Koppen's system of climatic classification (Kimmins 1987). Data recorded by an automated station on the site beginning in February 1990 showed rainfall averaged 1170 mm yr^{-1} and mean monthly air temperatures ranged from 10-27°C. Based on these measurements, estimates of potential evapotranspiration (PET) and actual evapotranspiration (AET) were calculated (Thornthwaite and Mather 1957). The 10-year averages indicate a water deficit occurs during much of the growing season (Fig. 1) as rainfall declines during the warmer months when PET is increasing. The average water deficit for the 10-year period was 123 mm yr^{-1}, with annual deficits ranging from 7 mm yr^{-1} in 1991 to 213 mm yr^{-1} in 1998. In 1998, plant water available in the profile was depleted to 77 mm, about 25% of the storage capacity of the soil. In the cooler months, increased rainfall and reduced PET combine to allow recharge of the profile by early December. After that excess water drains from the site with a fluctuating water table appearing during periods of high rainfall.

Experimental Details

The study was laid out following the design of a national network of long-term soil productivity research programme (Powers *et al.* 1990). This site was the first location in the network and was used to test the standard protocols and develop detailed methods for installation of other sites. The network plan called for a core set of nine treatments consisting of a factorial of three levels each of organic matter removal and soil compaction, replicated three times in several zones within a forest type. As the first site is not replicated, the compaction treatments are treated as blocks in this report. While this does not fit the exact criteria for experimental design, the use of compaction treatments as blocks allows testing of differences resulting from treatments that conform to the core treatments in the CIFOR 'Site management and productivity in tropical forest plantations' study (Tiarks *et al.* 1998). By age 10 years, the soil compaction had only a minor effect on tree growth on this site.

Figure 1. Ten year average of rainfall and estimated PET and AET for the experimental site



The core treatments consisting of three levels of organic matter removal are:

- **BL_0** All aboveground residue, understorey and litter removed.
- **BL_1** All aboveground parts of pines alone removed during harvest.
- **BL_2** Only merchantable stem removed, with all logging slash retained.

The amount of biomass removed from the BL_2 treated plots was 86 t ha^{-1} of wood and bark. An additional 13 t ha^{-1} of limbs and foliage was removed from the BL_1 plots. On the BL_0 plots, an additional 4 t ha^{-1} of understorey and forest floor was removed for a total of 103 t ha^{-1}.

The main plots are 65 x 65 m and planted at a 2.5 x 2.5 m spacing. Each of the nine 0.4 ha plots are split into two equal parts: weeds were allowed to develop on one half and herbicide was used to control weed growth in the other. Within each vegetation control subplot, there is a 20 x 50 m measurement plot consisting of 160 planting spots. The plots were planted in February 1990 using container grown seedlings raised from seed from 10 half-sib families of genetically improved loblolly pine. The families were planted in a stratified randomised pattern with family identity recorded.

Methods

Tree and Vegetation Measurements

Total tree height was measured annually for the first 10 years except age 8 and, beginning at age 5, dbh measurements were taken when heights were measured. Total volume (under bark), and dry weight of the wood, bark, branches and needles were calculated using equations developed by Baldwin and Feduccia (1982). Nutrient concentrations of wood, bark, needle and branch samples collected at harvest were used to estimate the amount of nutrients in the biomass at age 10 years. At ages 0, 5, and 10 years, forest floor and understorey samples were collected from four sample quadrats on each subplot. They were 1.25 m on each side with one corner anchored to a buffer row tree. The samples were categorised into logging residue or decayed wood, litter, including foliage from harvested pines, grasses and herbs, and hardwood trees and shrubs. Analysis of variance was used to test the statistical significance of differences in growth due to the treatments. Linear regression was used to test for significant relationships between soil bulk density and soil carbon content.

Soil Measurements

Soil samples for bulk density and chemical analysis were collected using core samplers of different diameters for the surface 30 cm and for deeper samples. A hand coring apparatus 60 mm in diameter (Ruark 1985) was used at ages 0, 5 and 10 years to take bulk density samples at the 0-10, 10-20, and 20-30 cm depths. The samples were collected from 10 random locations on each plot. Preliminary measurement of the variability indicated that seven samples are sufficient for determining bulk densities of the surface soil within a range of 0.05 g cm^{-3} at 90% probability. Deeper samples were collected at age 10 years from five locations in each plot using a 19 mm diameter soil sampling tube 1.8 m long (Veihmeyer 1929). These samples were collected in 30 cm increments from 30-180 cm.

Soil samples were air-dried and pulverised by hand to pass through a 2 mm sieve. Roots and rock fragments larger than 2 mm were saved and weighed from the three surface layers, but not from the deeper samples. At ages 0 and 5 years, the samples were bulked by plot and depth. At age 10 years, C, N, and S were determined on individual samples before bulking by plot and depth for other nutrient analysis. The concentrations of organic C, total N and total S were determined by a LECO 2000 elemental analyser in which the samples were combusted at 1350° C. Carbon and S were detected by infrared cells while the N was determined by a conductivity cell after reduction to N_2. Available P was extracted by Mehlich 3 and quantified colormetrically. Potassium and Ca were extracted with $BaCl_2$ and measured by atomic absorption spectroscopy. Carbon, N, and S in plant samples were determined by the elemental analyser. Plant samples were digested in nitric-perchloric acid heated to 190° C for determination of P colormetrically and K and Mg by atomic absorption.

Results and Discussion

Tree Growth

The retention of logging residue (BL_2) and weed control both increased the height of the loblolly pines after the first year (Fig. 2). Without weed control, the height growth difference between leaving all residue (BL_2) and removing all above ground biomass (BL_0) increased from 0.2 m at age 3 years to 0.8 m at age 7 after which the gain was maintained. With weed control, the response to residue retention was 0.4 m at age 3 years, but the largest difference was 0.7 m at age 6 years and then declined to 0.5 m at age 10 years. Compared to the estimate of height at a given age of the previous stand, the new plantation grew slower in the first 5 years but by age 10 years the height of the new stand when all above ground biomass was removed (BL_0) was about the same as the previous stand.

Removing all aboveground biomass improved survival by age 10 years (Table 1) although the difference was statistically significant only when weeds were not controlled. While leaving the forest floor and understorey intact (BL_1) did increase height and diameters by a small amount, the lower survival resulted in no volume difference compared to the total biomass removal. However, leaving all aboveground biomass did increase the volume of the pines by about 10 m^3 ha^{-1}, a statistically significant improvement. By age 10 years, the weed control treatment increased volume by 20 m^3 ha^{-1} regardless of the residue management. Together, leaving all the aboveground biomass and controlling the weeds resulted in about a 70% increase in volume compared to removing the logging residue and not controlling weeds.

Half-sib families had a significant effect on individual tree growth and total volume production (Table 2). The families with the largest volume per tree (TX 29 and MS 6) also were the families with the smallest and largest percentage of stem gall disease (*Cronartium quercuum* [Berk.] Miyable ex Shirai f. sp. *fusiforme*) respectively. Thus, in terms of total volume

Figure 2. Effects of residue retention and weed control on the height growth of loblolly pine for the first 10 years. Grey band is the height of the previous rotation estimated from stem analysis

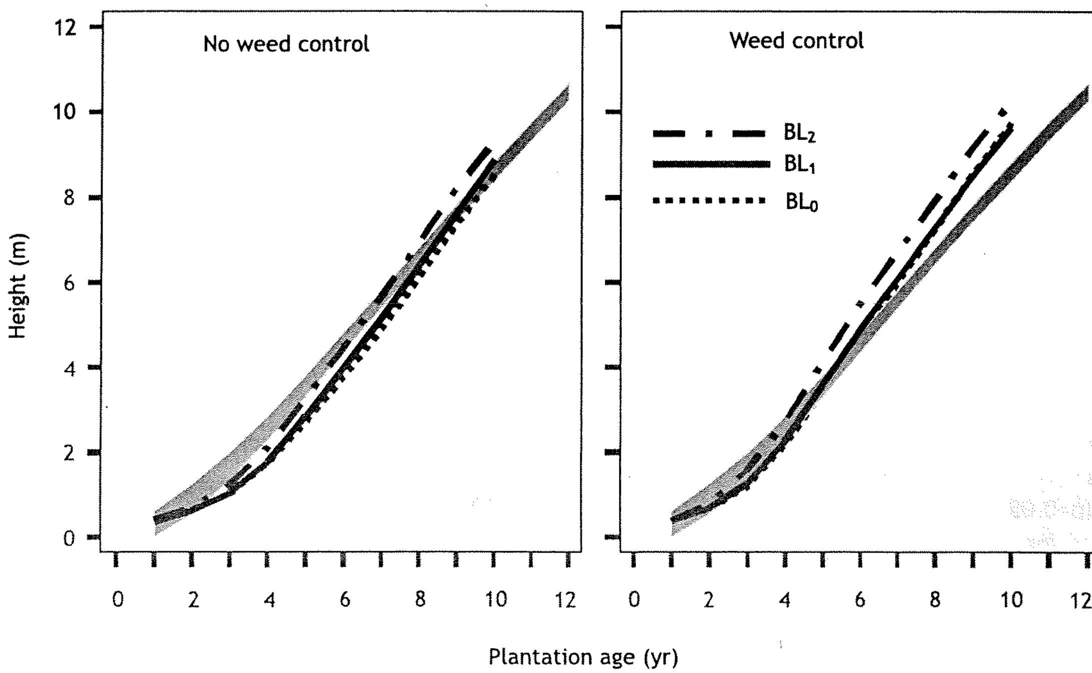


Table 1. Effects of residue management on the survival and growth of loblolly pine at age 10 years

Treatment	Survival	Height	Diameter	Volume (under bark)
	(%)	(m)	(cm)	(m^3 ha^{-1})
No weed control				
BL_0	78a	8.5a	11.7a	44.2a
BL_1	63b	8.9ab	12.5ab	42.0a
BL_2	69b	9.3b	13.1b	53.8b
Complete weed control				
BL_0	77a	9.7a	13.5a	65.7a
BL_1	74a	9.6a	13.6a	64.4a
BL_2	71a	10.2b	14.6b	74.9b

Values within the same column and weed control level followed by the same letter are not significantly different (alpha=0.10).

production, the TX 29 family was significantly better than any of the other selections. The family by residue interaction was not significant for any of the stand attributes and the family by herbicide interaction was significant only for the gall disease impact.

The heights of the pines on all of the plots were at least equal to the estimated height of the harvested stand at age 10 years, indicating that productivity is being maintained. Both the retention of aboveground biomass and weed control increased pine heights above the previous stand, indicating improved site productivity resulting from management activities. However, because of improved planting conditions, survival was better on plots where all residues had been removed. Thus, even though individual tree size

Table 2. Growth of 10 half-sib families at age 10 years averaged over three residue management treatments and two weed control levels

Source and number	Height (m)	Dbh (cm)	Volume (m^3 $tree^{-1}$)	Total volume (m^3 ha^{-1})	Diseased (galls) (%)
LA 14	9.56	13.3	0.051	60.9	14.2
LA 28	9.27	13.0	0.047	52.6	11.8
LA 31	9.07	12.2	0.044	45.2	8.0
LA 33	9.29	12.8	0.046	57.9	4.2
TX 7	9.26	13.4	0.050	58.5	4.9
TX 17	9.27	13.3	0.050	52.3	6.6
TX 29	9.60	13.4	0.053	66.6	3.8
TX 36	9.58	13.2	0.051	62.3	6.9
MS 6	9.49	13.4	0.053	58.1	26.4
MS 26	9.40	13.6	0.052	60.6	12.8
Mean	9.38	13.2	0.050	57.5	10.0
LSD ($p=0.05$)	0.22	0.5	0.004	8.2	4.4
Interaction[a]	NS	NS	NS	NS	0.006

[a] refers to the significance level of the herbicide by family interaction; NS=not significant.

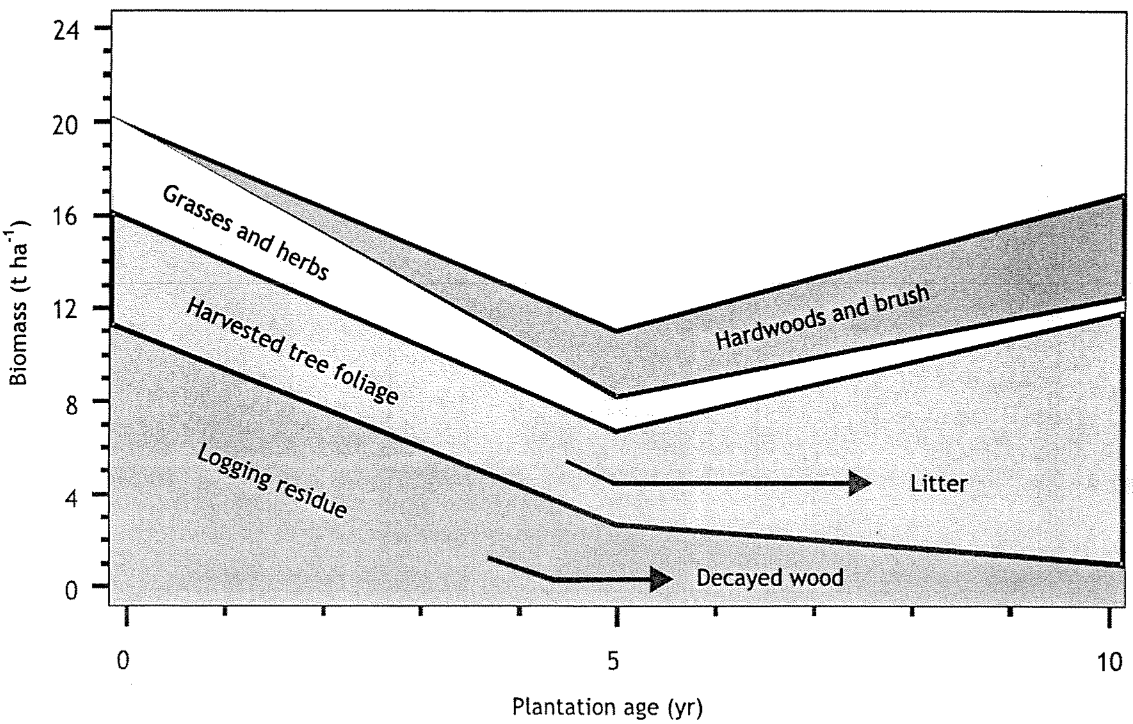
increased when understorey and litter were retained on site, volume production was not affected at age 10 years. The positive effect of retaining logging residues on this site is most likely from the nutrients released rather than water conservation by the mulching effect. The water deficit was high in some years, but pine growth in those years was not noticeably affected. Thus the water storage capacity of the soil profile seems to be sufficient to sustain growth in most years. Large differences in growth and disease impact were measured between families of trees, but genetic source did not interact with treatments in agreement with the results of hybrid pines in Queensland (Simpson 2000).

Understorey Response

Decomposition reduced the woody material in limbs and tops left as logging residue to 0.7 Mg ha^{-1} by age 10 (Fig. 3). The biomass of decaying wood at age 10 was no longer affected by residue treatment because dead limbs falling from the new plantation were beginning to add to the decaying wood component. The amount of litter, including all non-woody material on the forest floor, changed little in the first 5 years, but by age 10 years litter was the primary component of the forest floor and was the only one significantly affected by the residue management treatments. The biomass of the litter ranged from 7.6 Mg ha^{-1} for the BL_0 treatment to 8.0 Mg ha^{-1} for the BL_1 treatment and to 10.9 Mg ha^{-1} for the BL_2 level. As the stand developed and crown closure occurred, the biomass as grasses and herbs declined to 0.8 Mg ha^{-1}. The amount of hardwood and brush had increased significantly by age 10 years, averaging 2.5 Mg ha^{-1} but was not significantly affected by the residue management treatments.

The increase in hardwood and brush resulted from the changing in fire regime from a prescribed burn every 3 years to none in the first 10 years. Because the litter includes the accumulation of fresh and partially decomposed foliage from several years, the amount of litter at age 10 years is larger than the amount of foliage deposited by the harvested stand. As residue retention increased the amount of litter by increasing the size of the pines, the benefit of residue retention might be even larger at the establishment of the next rotation.

Figure 3. Biomass in logging residue and understorey at harvest and in understorey and litter at ages 5 and 10 years for the BL_2 treatment without weed control



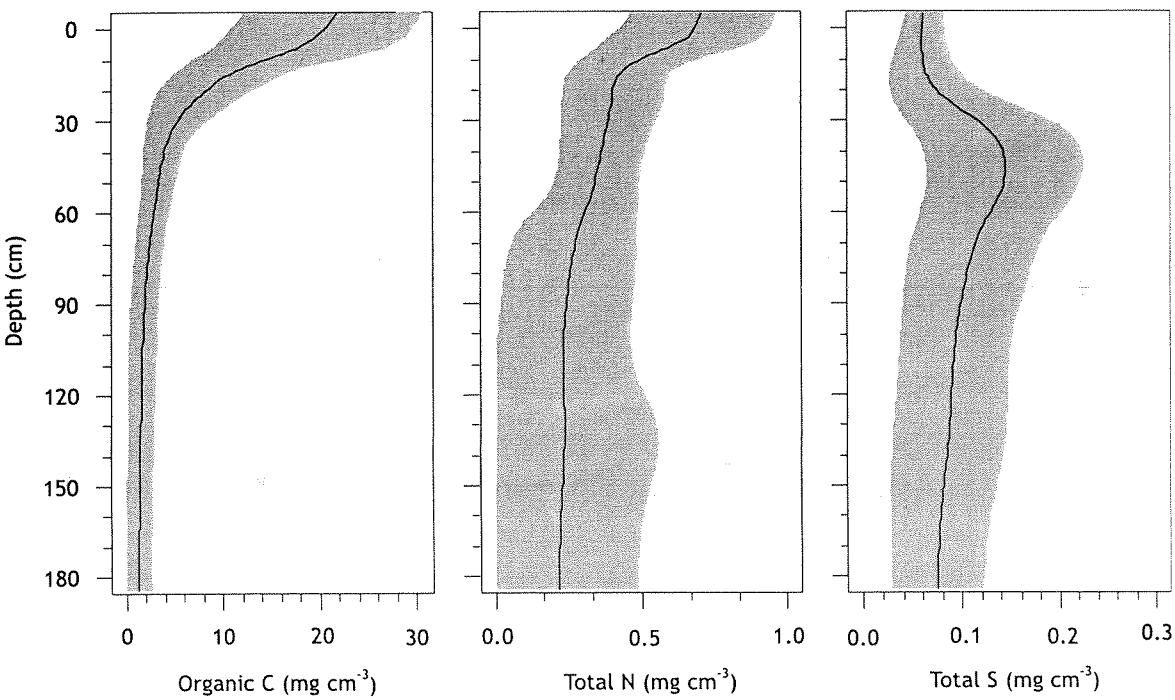
Soil Bulk Density and Organic Carbon Distribution

Ten years after planting, the treatments had little effect on soil bulk density, C or other nutrients. Averaged across all treatments, the soil bulk density increased with depth averaging 1.27 g cm^{-3} at the 0-10 cm depth to 1.80 g cm^{-3} at the 150-180 cm depth. The soil densities also varied widely within a depth with the bulk densities ranging from 0.71 to 1.50 g cm^{-3} in the surface and from 1.43 to 2.09 g cm^{-3} at the 150-180 cm depth. As expected, the concentration of soil organic carbon decreased from 15.0 g kg^{-1} in the surface to 0.7 g kg^{-1}. Because of the increasing bulk density with depth in these soils, the C, N, and S distributions are shown as mass per unit volume (Fig. 4). The amount of C decreases rapidly with depth to about 60 cm but measurable quantities were found at the deepest sampling depth. The C was most variable at the surface but was fairly uniform below 60 cm. The mean N concentration on a volume basis declined rapidly with depth like C, but the N was more variable. Thus at 180 cm, the 90% confidence internal for N ranges from 0 to 0.5 mg cm^{-3}. The large variability in N at the deeper depths may be associated with an accumulation of NH_4^+ on the exchange complex which would have been detected by the methods used.

Sulfur values were the largest at about the 45 cm depth where the clay concentrations are also the highest.

Soil organic carbon can affect soil bulk densities by two mechanisms. First, increased soil organic carbon will reduce bulk densities in most soils because the particle density of organic carbon is much lower than the particle density of most inorganic soil constituents. Second, increased organic matter may improve soil structure increasing the volume of soil occupied by voids. By assuming particle densities of 1.30 g cm^{-3} for soil organic matter and 2.65 g cm^{-3} for minerals

Figure 4. Distribution of C, N, and S in soil 10 years after plantation was established. Shaded areas are 90 % confidence intervals



(Adams 1973), the soil porosity or portion of soil in voids was calculated for each soil sample. The estimated porosity doubled from about 0.26 to 0.52 as the amount of soil organic matter increased from nil to 30 g kg^{-1} (Fig. 5). Since this analysis is based on all depths, confounding is possible as both porosity and C decrease with depth. However, the interaction term between depth and the C by porosity regression is not significant. Also, the C by porosity fit is significant for each depth individually.

Because soil organic carbon affected porosity, the normal practice of bulking samples that are from the same depth and plot before determining organic carbon may lead to errors. If the relationship is affected by the treatments, the amount of carbon in the profile may be biased if samples are combined before measurements are made. In this study, combining samples before carbon was measured would have underestimated the amount of carbon in the profile for all treatments. The underestimation was largest in both biomass removal and weed control treatments. However, the differences were small, ranging from 0.6% of carbon in the profile in the BL_2 treatment without weed control to 2.9% in the BL_0 treatment with weed control. These differences amount to about a 1.2 Mg ha^{-1} error in the total carbon in the profile. In this study, combining samples before the measurement of carbon was acceptable. However, this potential source of error should be considered if a treatment that may change soil porosity, such as tillage, is part of the experiment.

Carbon and Nutrient Distributions

The only treatment that had an effect on the amount of carbon in the surface 10 cm of soil was weed control and the difference was statistically significant only at age 5 years (Fig. 6). On plots not receiving weed control, the amount of organic carbon increased from 20.8 Mg ha^{-1} at harvest to 22.5 Mg ha^{-1} at age 5. At the same time, controlling weeds reduced the amount of carbon to 17.5 Mg ha^{-1}. By age 10 years,

Figure 5. Effect of soil organic carbon content on soil porosity or fraction of soil occupied by voids

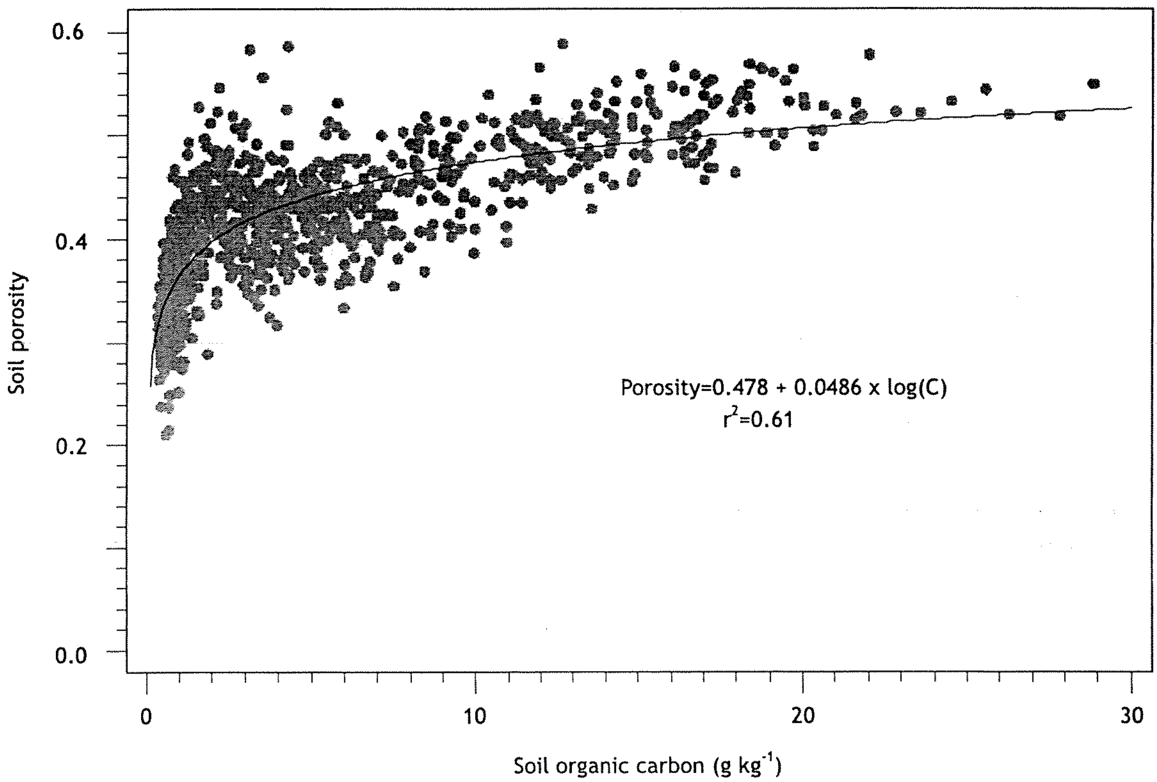
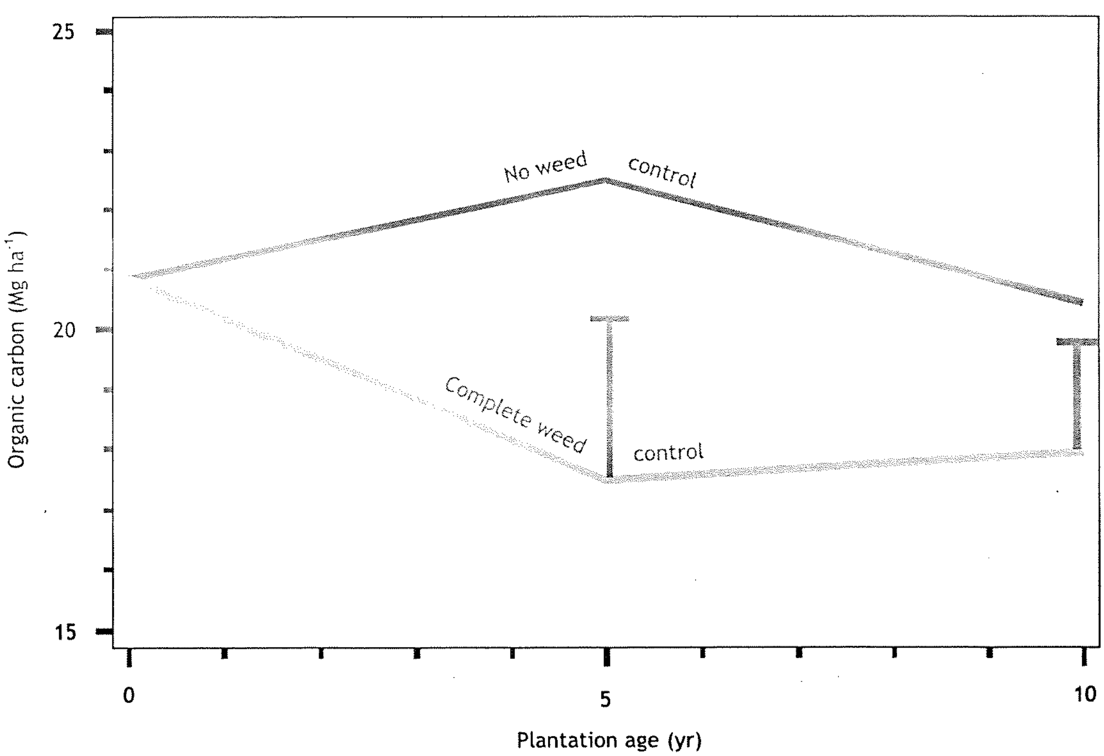


Figure 6. Effects of weed control on soil organic carbon in surface 10 cm of soil. Vertical bars represent LSD for ages 5 and 10 years (p=0.05).



the effects of both treatments had diminished but the amount of organic carbon was still significantly different.

While the weed control had a significant impact on the growth of the pines, the total amount of organic carbon in the system was not affected (Table 3). Weed control increased the fraction of carbon that was in the aboveground portion of the pines from 18.9 to 25.7%. However, when weed control was applied, the fraction in the soil decreased from 75.3 to 68.9%. The same effect of the weed control was noted for the other nutrients. For example, weed control increased the amount of K in the pine biomass by 8.2 kg ha^{-1} while the amount of K in the surface 30 cm of soil was reduced by 7.5 kg ha^{-1}. The overall decrease of 8.1 kg ha^{-1} in all components is only 1.8% of the K in the system, well within measurement error.

The soil is the largest reservoir of the organic carbon and nutrients. More than two thirds of total carbon and more than 95% of the nitrogen on the site is in the soil. Because of this large buffer, management practices may cause only small changes in concentrations in the soil. However, as the availability of nutrients such as P is difficult to measure, these small changes may lead to growth declines if corrective action is not taken. When weeds are controlled, the pine trees are larger. Even if the concentration of nutrients is not affected, harvesting will remove a relatively larger amount of nutrients. For example, weed control reduced the amount of K in the forest floor and understorey but increased the amount of K in pines from 32.8 to 41.0 kg ha^{-1}. As about 11% of the total K on the site is in aboveground biomass, removals during harvest and site preparation may reduce site productivity. As critical limits for nutrients are approached, pine growth will decline rapidly as the reserves

Table 3. Carbon and nutrients in pine biomass, understorey, and soil of 10-year-old loblolly plantation

Component	C		N		P		K		Ca	
	Ho[a]	H1[b]	Ho	H1	Ho	H1	Ho	H1	Ho	H1
	(Mg ha^{-1})		(kg ha^{-1})							
Needles	3.1	3.9	72.2	93.4	4.86	6.04	21.1	24.4	8.5	11.1
Branches	3.6	4.9	11.0	15.1	1.20	1.64	4.0	5.5	10.0	14.3
Bark	3.1	4.3	8.9	12.4	1.34	1.89	2.6	3.6	13.4	18.8
Wood	8.7	12.8	9.5	14.1	1.70	2.52	5.1	7.5	8.6	12.8
Woody understorey	1.2	0.2	12.3	2.2	0.53	0.12	5.0	1.1	8.9	0.9
Herbaceous understorey	0.4	0.1	5.3	1.0	0.27	0.05	3.2	0.4	3.1	0.5
Litter	3.8	4.7	68.0	62.1	2.62	2.71	6.0	5.6	59.3	48.0
Decaying wood	0.3	0.4	2.6	5.0	0.08	0.12	0.2	0.4	2.4	2.1
Roots 0-30 cm	4.4	4.1	N.D.[c]	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Soil 0-30 cm	38.0	34.2	1546.7	1398.3	N.D.	N.D.	65.1	57.6	791.8	710.3
Soil 30-180 cm	31.4	31.2	3768.9	4197.4	N.D.	N.D.	327.7	330.7	1207.1	1369.3
Total	98.0	100.8	5505.4	5801.0	N.D.	N.D.	440.0	436.8	2113.1	2188.1
% in pines	18.9	25.7	1.8	2.3	N.D.	N.D.	7.5	9.4	1.9	2.6
% in under/ff[d]	5.8	5.4	1.6	1.2	N.D.	N.D.	3.3	1.7	3.5	2.4
% in soil	75.3	68.9	96.6	96.5	N.D.	N.D.	89.2	88.9	94.6	95.0

[a] no weed control; [b] total weed control; [c] not determined; [d] understorey and forest floor.

are depleted. On these nutrient deficient sites, conservation of nutrients and replacement by fertilisation are important management considerations.

Conclusions

At age 10 years, the replanted pines were as tall or taller than the pines in the original stand at a comparable age. While comparisons between rotations are difficult, these results indicate that pine production on this site is sustainable. Leaving all the aboveground logging residue and weed control increased the heights of the pines compared to the previous rotation. Removal of the forest floor resulted in smaller trees, but volume production was not reduced because of better survival. Weed control increased pine growth more than residue retention, and the effects of both management options were additive. Differences in the productivity of half-sib families indicate that some genetic gain is possible. Except for the incidence in stem gall disease, genetic gain was independent of residue retention and weed control.

As the amount of logging residue increased, the amount of litter under the stands at age 10 years increased. However, the increased pine growth and litter accumulation did not affect the amount of organic carbon (OC) in the soil. Weed control reduced the amount of OC in the surface 10 cm of soil at age 5 years, but this difference was smaller and no longer statistically significant by age 10. At low levels of OC, small increases in OC increased the soil porosity. At OC levels greater than about 5 g kg^{-1}, the effect of OC on porosity was small.

At age 10 years, neither residue retention nor weed control affected the amount of nutrients in the ecosystem, including the soil to 180 cm. Weed control did increase the fraction of nutrients that had accumulated in the pines and subject to removal by harvesting. Thus, as the intensity of management increases, the importance of retaining logging residue on the site for supporting long-term productivity will increase.

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