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Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine

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Abstract

Short- and long-term effects of high and low site preparation intensity, fertilization at planting and vegetation control on growth and stand development were examined in a study that was established on six sites in southeastern USA. The study was established in 1979–1980, and growth after the 18th growing season is reported. The high-intensive site preparation improved long-term stand volume growth. Evidence suggests that the main long-term effect of the intensive site preparation was a reduction in competition from hardwoods. Herbicide treatment improved seedling establishment and early growth, but growth during the last period of measurements (14–18 years after planting) were lower in the herbicide-treated plots as compared to plots without herbicide treatment when herbicides were combined with intensive site preparation. Fertilization at planting, in combination with high-intensive site preparation, improved volume growth during the first 10 years after planting, while fertilization at planting in combination with low-intensive site preparation had little effect on volume growth. The hypothesis that low variability in the seedling stage due to intensive site preparation will lead to low variability in the mature stands with a subsequent reduction in self-thinning was examined. The low site preparation intensity had higher coefficient of variations of stem volumes, and higher mortality. However, the difference in mortality was probably partly a result of differences in competition from hardwoods, and it was not possible to separate the importance of reduced variability from reduced competition from hardwoods. Fertilized plots had lower variability than non-treated control plots but there was no significant difference in mortality between the two treatments. Therefore, it was concluded that reduced variability in the seedling stands, as a result of intensive regeneration methods that reduces environmental heterogeneity, reduces the variability in the mature stands. However, it could not be inconclusively proved that lower variability in the mature stands will result in reduced or postponed self-thinning.

Keywords: *Pinus taeda* L.; Southeastern USA; Self-thinning

1. Introduction

Studies of the long-term impact of various regeneration methods are limited since plot sizes are often too small to study treatment effects beyond the establishment phase. In the southeastern United States,

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interest in the long-term effects of slash disposal, cultivation, fertilization and vegetation management on growth and yield of loblolly pine (*Pinus taeda* L.) developed during the 1970s. In response to these interests, the North Carolina State Forest Nutrition Cooperative initiated a study in the late 1970s to examine the long-term influence of site preparation, fertilization and vegetation management, and their interactions on loblolly pine.

Four types of long-term growth response to early cultural treatments have been described (Hughes et al., 1979; Morris and Lowery, 1988). Type A response occurs when growth gains on treated areas continue to increase throughout the rotation. Type B response occurs when growth gains achieved early in the rotation are maintained but do not continue to increase after an initial response period. Type C response occurs when early growth gains are subsequently lost, and a type D response occurs when early growth on treated areas fall below levels observed on non-treated areas. The effect of various regeneration methods may be any of the above-described types depending upon site characteristics and how the regeneration methods are applied.

Site preparation will result in a type B response if the only effect is a reduction in the abundance of competing herbaceous vegetation, or if the effect is a short-term improvement of the rooting volume (Sutton, 1995; Nilsson and Örlander, 1999) while a type A response may occur if site preparation also reduces competition from hardwoods (Glover and Zutter, 1993; Zutter and Miller, 1998; Cain, 1999). Site preparation can also result in a type C or type D response if the treatment involves removal of nutrients (Fox et al., 1988).

Herbicide treatments most often result in type B responses with early growth gains and no subsequent increase in production (e.g. Lauer et al., 1993; Morris et al., 1993; Nilsson and Örlander, 1999; Mason and Milne, 1999). However, if herbicides are successful in controlling hardwoods, or if use of herbicides enables planted crop trees to occupy the site before the establishment of competing hardwoods, a type A response may occur. Furthermore, because the nutrient uptake of the ground vegetation is decreased by herbicide treatments, leakage of nutrients may occur because the combined uptake of the planted seedlings and remaining ground vegetation are less than net mineralization and a type C response can be the result (Smethurst and Nambiar, 1989; Vitousek et al., 1992; Allen and Lein, 1998). Finally, a type D response for herbicide treatments has been reported as a result of herbicide damage (Allen, 1996).

Fertilization may result in either short- or long-term increases in nutrient availability and increased growth of planted seedlings/trees depending on the element, application rates and site characteristics. Phosphorus (P) fertilization on P-deficient soils typically results in long-term increases in P availability, and a type A response (Ballard, 1972; Pritchett and Comerford, 1982; Schmidtling, 1984; Gent et al., 1986), while nitrogen fertilization often leads to a more short-term type B response (Hynynen et al., 1998). Fertilization at the time of planting may also lead to a type D response. If competing vegetation gains more from fertilization than crop trees, growth of the preferred crop trees may be less than if fertilizers had not been added (Allen, 1996; Allen and Lein, 1998).

In addition to the effects on growth, regeneration methods may also affect stand development in terms of size variability. Within populations, variability in size develops as a function of factors causing variation in growth between the planted seedlings, e.g. heterogeneous environment, variation in genetics and seedling conditions, damages, etc. (Weiner and Thomas, 1986). By reducing variability in seedling stands, variability may be reduced in mature stands (Lieffers and Titus, 1989). Self-thinning is often the outcome of size hierarchies where large individuals suppress the smaller ones to the point where they no longer can sustain their carbohydrate needs for respiration. Therefore, it is possible that populations with less variability prior to crown closure will undergo delayed self-thinning compared to stands that originates from seedling stands with large variability in sizes.

The objectives of this study were to examine effects of site preparation intensity, herbicide treatments and fertilization at planting on short- and long-term growth responses on planted loblolly pine stands. In addition, the effects of the various regeneration methods on the development of variability were examined, and the hypothesis that low variability in the seedling stage will lead to low variability in the mature stands with a subsequent delay in self-thinning was examined.

2. Material and methods

Originally, 19 regeneration trials to study long-term impact of various regeneration methods were established by members of the North Carolina State Nutrition Cooperative in southeastern USA. However, because a complete data set of heights and diameters only existed for six of the sites, these were selected for this study. The selected sites were located from eastern Virginia to southern Alabama (Fig. 1). Four of the sites were on well-drained soils while two were poorly drained (Table 1).

Each installation received a factorial combination of two levels of each site preparation, fertilization and herbicide treatment. These treatments were applied in a split-plot design with two site preparation treatments as main plots and fertilizer × herbicide treatments as subplots (Fig. 1). All sites were originally established with four blocks. However, on site 2401 one block had to be dropped due to fire. Treatment plots were 28.8 × 28.8 m, with 12 rows of 12 seedlings planted at a 2.4 m spacing. The internal 8 × 8 rows served as measurement plots. Site preparation methods varied by site and interest of the landowner but included one of low intensity and one of high intensity (Table 2). The low site preparation (LSP) included chopping with a rolling drum pulled behind a bulldozer, broadcast burning, or a combination of these treatments except for site 2402 where LSP was shearing with a bulldozer mounted KG-blade and piling with a bulldozer

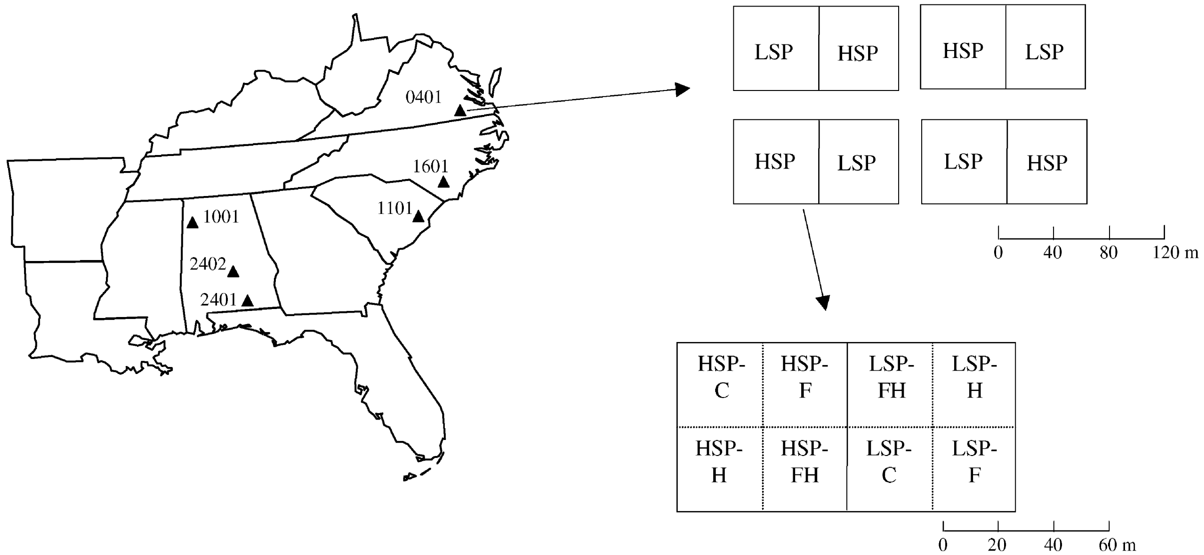

Fig. 1. Location and layout of experimental plots. Treatments were: low-intensive site preparation (LSP); high-intensive site preparation (HSP); control (C); fertilization (F); herbicide (H); herbicide + fertilization (HF).

Table 1
Description of the experimental sites

Site	Soil type	Subsoil texture	Drainage	Previous stand
0401	Typic Hapludult	Loam	Well	Pine hardwood
1001	Typic Hapludult	Clay loam	Well	Pine hardwood
2401	Arenic Plinthic Paleudult	Loam	Well	Natural loblolly pine
2402	Typic Hapludult	Clay	Well	Loblolly pine plantation
1101	Aeric Ochraquult	Clay	Poorly	Natural longleaf pine
1601	Typic Humaquept	Sandy loam	Poorly	Pine hardwood

Table 2
Description of the treatments

Site	Site preparation intensity		Planted	Hexazinone applications (kg ha^{-1})	Fertilization
	Low	High			
0401	Chop, burn	Shear, pile, disc	March 1979	0.84 (May 1979 and 1980)	June 1979
1001	Burn	Shear, pile, disc	April 1979	1.12 (June 1979 and 1980)	June 1979
2401	Chop, burn	Shear, pile, disc	March 1979	0.94, 0.63 (May 1979 and 1980)	August 1979
2402	Shear pile	Shear, pile, bed	December 1979	0.84 (July 1980 and 1981)	May 1980
1101	Chop	Chop, bed	March 1979	1.12 (May 1979 and 1980)	April 1979
1601	Burn	Burn, double bed	March 1979	1.40, 1.88 (May 1979 and 1980)	April 1979

mounted root rake. The high site preparation (HSP) treatments were shearing with a bulldozer mounted KG-blade and piling with a bulldozer mounted root rake, followed by disc harrowing on the well-drained sites except for site 2402 where HSP was shearing, piling, and bedding instead of disc harrowing. On the two poorly drained sites, the HSP treatments were chopping followed by bedding (1101) and broadcast burning followed by two passes of a bedding plow (1601). Site preparation was done during the summer or fall before planting. The fertilizer treatments included a control (no fertilizer) and nitrogen (N) and phosphorus (P) applied as diammonium phosphate (DAP) applied at or immediately following planting at a rate of 280 kg ha^{-1} (N = 45 kg ha^{-1}; P = 56 kg ha^{-1}). Fertilizer was broadcast on the soil surface in a 1.2 m band centered on each planted row. Since this treated band represented one-half of the plantation area, the actual fertilizer rate within this band was 560 kg ha^{-1}. Herbicide treatments included a control (no herbicides used) and a banded (1.2 m) application of hexazinone applied once during each of the first two growing seasons following planting. Hexazinone (Velpar™) rates varied depending on soil type and are expressed as the actual application rates in the treated band (Table 2).

Total height and diameter at breast height (1.4 m; DBH) were measured on all surviving trees during the dormant season following the second, fourth, sixth, eight, tenth, twelfth, fourteenth and eighteenth growing season. These data provided the basis for calculating growth measures and survival percentages. Volumes were averaged on a plot basis to provide measures of individual tree growth. Individual tree volumes were summed on a plot basis to provide stand growth estimates that integrated treatment effects on survival and mean tree size. Stem wood volume was calculated as

$$V = 0.00748 + (0.0000353 \times D^2 \times H^2)$$

where V is the total outside bark volume in cubic meters (Shelton et al., 1984).

Coefficients of variation (CV) for stem volumes after the sixth–eighteenth growing season were calculated for each plot and averaged for each treatment and year.

Standing volume, volume growth, survival and CV for each site preparation intensity were analyzed using ANOVA for a 2×2 factorial structure in a randomized complete block design. The analysis included tests of the main effects of the herbicide and fertilization treatments and their interaction. Preliminary analyses indicated significant interactions among site preparation, fertilization and herbicide treatments. Therefore, to aid in the interpretation of fertilizer and herbicide effects, separate analyses were done for each site preparation intensity. Effects of site preparation intensity averaged across the fertilizer and herbicide treatments were analyzed using ANOVA for split-plot design with site being the main effect, and site preparation being the sub-plot effect. In order to analyze the influence of stand structure in the seedling stand on future mortality, regression functions for mortality (percent of stems) between ages 4 and 18 were estimated with and without the CV for height growth between ages 2 and 4 as an independent variable. In the regression functions, mean height and height growth for the tallest 5% of the seedlings at age 4, and number of stems per hectare were also used as independent variables. This analysis was only done for the high-intensity site preparation treatments because mortality in the low-intensity site preparation was influenced by competition from hardwoods.

3. Results

Four years after planting, stem volume per hectare was significantly greater for high-intensive site preparation (HSP) than for low-intensive site preparation (LSP) (Table 3). Furthermore, the fourth year volume was significantly increased by the herbicide and fertilization treatments when combined with HSP but not when combined with LSP (Table 3). Fertilization, in combination with HSP, significantly increased volume 18 years after planting (Fig. 2, Table 3). Volume 18 years after planting was not significantly affected by herbicide, but there was a tendency for a positive herbicide treatment response for the LSP plots. Over the 18-year study period, mean annual increments ranged from 11.3 $m^3 ha^{-1}$ per year for the control treatment in combination with LSP to 15.6 $m^3 ha^{-1}$ per year for the herbicide + fertilization treatment in combination with HSP. The variation between sites in response to the various fertilization and herbicide treatments was larger for LSP than for HSP (Table 4). For HSP, standing volumes after 18 years were highest for the fertilizer alone or herbicide + fertilizer treatments on all sites but two (1601 and 1001).

Current annual stem volume increment (CAI) was significantly higher for HSP than for the LSP during the first 14 years of the study (Fig. 2, Table 3). There was a positive effect of the herbicide treatment on CAI during the first 10 years after planting when herbicide use was combined with LSP but only during the first 8 years when combined with HSP. Fertilization had a significant positive effect on CAI during the first 10 growing season after planting when combined with HSP but no significant effect on CAI at any time when combined with LSP (Fig. 2, Table 3). During the last measurement period (15–18 years after planting), the herbicide treatment in combination with HSP had a statistically significant negative effect on CAI.

Mortality during the first 4 years after planting was higher for LSP than for HSP resulting in significantly lower stand density for LSP (Tables 5–6). Eighteen years after planting, the same rankings and absolute differences in stand density between the site preparation treatments still remained. Herbicide use had lower survival after 4 years for both LSP and HSP (Tables 5–6). After 18 years, survival for trees in the herbicide-treated plots was significantly lower than for other treatments when combined with HSP but not when combined with LSP. There was no significant difference in post-establishment mortality (between years 4 and 18) among any of the treatments.

The coefficient of variation of stem volume (CV) varied between site preparation treatments. For LSP plots, CV increased rapidly until standing volume reached 100 $m^3 ha^{-1}$ (about age 10) and decreased slightly thereafter, while CV increased during the

Table 3
Probability values from the analysis of variance for standing volume and standing volume growth for the various site preparation intensity, herbicide and fertilization treatments (for description of treatments, see Fig. 1)

Years after planting	Standing volume		Periodic volume growth					
	4	18	5–6	7–8	9–10	11–12	13–14	15–18
LSP intensity								
Herbicide	0.2312	0.0539	0.0110[a]	0.0049[a]	0.0460[a]	0.2281	0.5287	0.1542
Fertilization	0.3442	0.4399	0.7931	0.4504	0.1502	0.4021	0.5461	0.9555
Herbicide × fertilization	0.8850	0.5048	0.8792	0.7050	0.8647	0.5904	0.6167	0.2245
HSP intensity								
Herbicide	0.0056[a]	0.9147	0.0001[a]	0.0031[a]	0.5738	0.4606	0.4919	0.0012[a]
Fertilization	0.0221[a]	0.0060[a]	0.0001[a]	0.0028[a]	0.0070[a]	0.0585	0.2193	0.2400
Herbicide × fertilization	0.9647	0.8296	0.2517	0.3108	0.4443	0.2769	0.3614	0.9843
Site preparation	0.0001[a]	0.0001[a]	0.0001[a]	0.0001[a]	0.0001[a]	0.0001[a]	0.0001[a]	0.4068

[a] Statistically significant effects ($P < 0.05$).

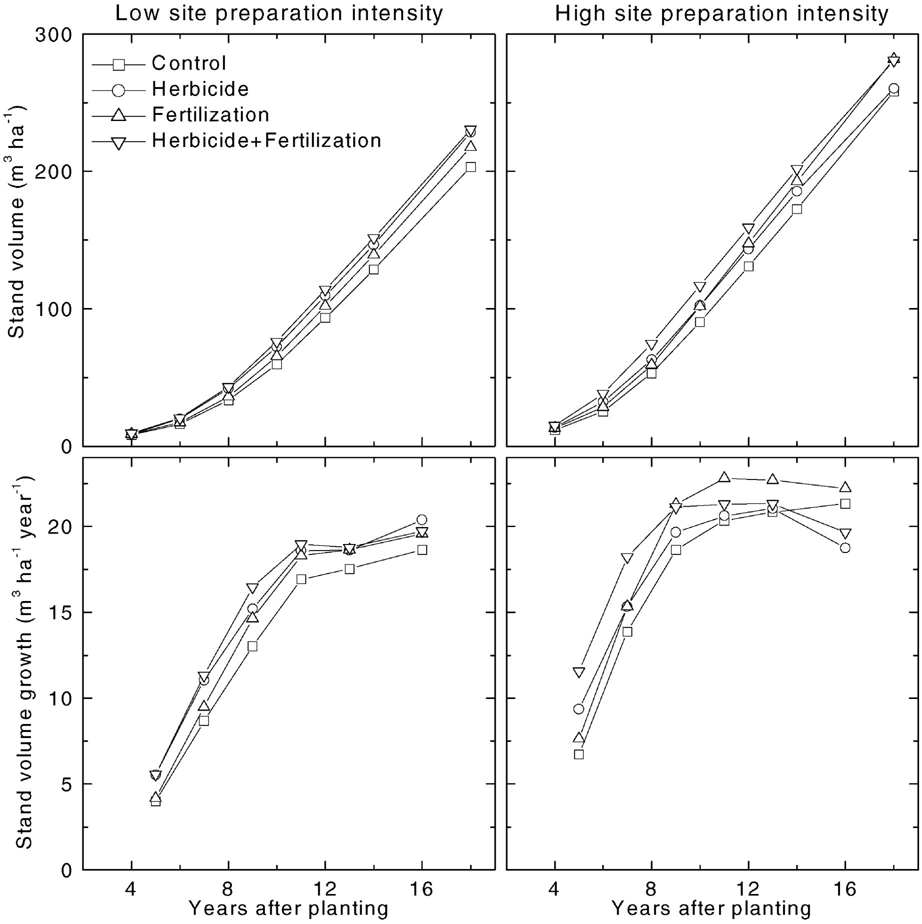

Fig. 2. Development of standing volume ($m^3\ ha^{-1}$, upper) and stand volume growth ($m^3\ ha^{-1}$ per year, lower) for low-intensive (LSP, left panels) and high-intensive (HSP, right panels) site preparations. Each site preparation treatments were divided into four treatments; untreated control, herbicide treatment, fertilization at the time of planting and a combination of herbicide and fertilization. Each point represents average value of six sites.

Table 4
Standing volume per hectare ($m^3\ ha^{-1}$) 18 years after planting for the various site preparation, herbicide and fertilization treatments (for descriptions of treatments, see Fig. 1)[a]

Site	LSP intensity				HSP intensity			
	Control	Herbicide	Fertilization	Herbicide× fertilization	Control	Herbicide	Fertilization	Herbicide× fertilization
All	203	228	218	231	258	261	282	281
0401	247	241	202	251	279	231	306	311
1001	196	179	165	185	239	275	269	258
2401	118	91	192	131	143	159	216	185
2402	210	254	255	287	248	247	267	304
1101	174	191	237	235	275	270	294	279
1601	253	382	249	270	335	356	322	324

[a] Average values for all sites as well as values for individual sites are given.

Table 5
Survival (seedlings ha^{-1}) of planted loblolly pine 4, 10 and 18 years after planting for the various site preparation intensity, herbicide and fertilization treatments (for description of treatments, see Fig. 1)

	Years after planting		
	4	10	18
LSP intensity			
Control	1134	1069	975
Herbicide	1067	1006	916
Fertilization	966	906	839
Herbicide × fertilization	983	934	863
HSP intensity			
Control	1380	1283	1207
Herbicide	1283	1215	1112
Fertilization	1440	1359	1258
Herbicide × fertilization	1243	1171	1081

whole study period for HSP treatments (Fig. 3). CV was statistically higher for LSP as compared with HSP from the eighth to the fourteenth growing season, and there was a tendency for higher CV on the LSP plots at year 18 (Fig. 3, Table 6). With LSP, herbicide and fertilization treatments alone had no statistically significant effect on CV except for 6 years after planting. With HSP, fertilization significantly reduced CV at age 18 while herbicide had no significant effect on CV. Furthermore, there were significant or almost significant interactions between fertilization and herbicide when they were combined with LSP. When herbicides and fertilizers were used together, CV was about the same as for the control while it was higher when herbicides and fertilizers were used alone.

The coefficient of variation for height growth between ages 2 and 4, together with the number of stems, and height and height growth of the tallest 5% of trees at age 4, explained 59% of the variability in mortality between ages 6 and 18 (Table 7). A similar regression without CV as independent variable only explained 28% of the variation in mortality.

4. Discussion

At the end of the study period, standing volumes were higher in HSP than in LSP due in part to better survival and early growth but also due to increased individual tree growth throughout the 18 years. For example, at the end of the sixth growing season, standing volume in the LSP-control treatment was as high as standing volume in four-and-a-half-year-old stands in the HSP-control treatment. At age 18, standing volume in LSP-C was as high as standing volume in 15-year-old stands in the HSP-C treatment. Thus, the comparison between LSP-C and HSP-C indicates a type A response where growth gains continue to increase throughout the rotation. Mason and Milne (1999) concluded that if large differences in standing volume occur at the start of a measurement period, then analysis of variance of growth at a later age may not be the best way of distinguishing between

Table 6
Probability values from the analysis of variance for coefficient of variation and survival (stand density) for the various site preparation intensity, herbicide and fertilization treatments (for description of treatments, see Fig. 1)

Years after planting	Coefficient of variation						Survival	
	6	8	10	12	14	18	4	18
LSP intensity								
Herbicide	0.0001[a]	0.4831	0.4209	0.3006	0.5405	0.6750	0.0137[a]	0.0620
Fertilization	0.0179[a]	0.4891	0.8798	0.7621	0.5750	0.6393	0.5747	0.6782
Herbicide × fertilization	0.0391[a]	0.0497[a]	0.0144[a]	0.0828	0.0638	0.0707	0.8302	0.4561
HSP intensity								
Herbicide	0.2656	0.1411	0.1180	0.3244	0.4678	0.4593	0.0054	0.0085
Fertilization	0.5642	0.2626	0.1207	0.1207	0.0870	0.0454[a]	0.8653	0.7351
Herbicide × fertilization	0.6529	0.8048	0.4131	0.8220	0.7587	0.9390	0.2597	0.3358
Site preparation	0.8399	0.0014[a]	0.0005[a]	0.0007[a]	0.0034[a]	0.0586	0.0001[a]	0.0001[a]

[a] Statistically significant effects ($P < 0.05$).

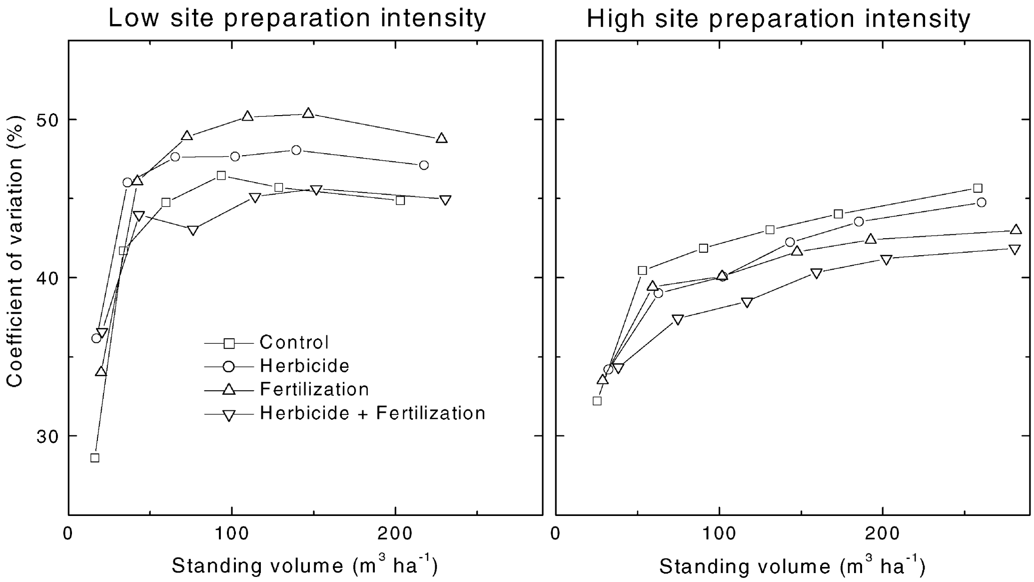

Fig. 3. Coefficient of variation (CV) of stem volumes over standing stem volume (m^3 ha^{-1}), the various site preparation treatments, herbicide and fertilization treatments (for descriptions of treatments, see Fig. 1). Each point is the average value of six sites.

response types. Instead, either inspection of graphs or careful evaluation of fitted models need to be used to determine whether growth differences occur following equivalent starting values at different ages. Current annual stem wood increment (CAI) was higher for the HSP than for LSP when compared at the same standing volume (Fig. 2). Consequently, CAI was higher during the whole study period when the comparison was equalized in terms of standing volume in the beginning of the measurement period. Comparing the fertilization and herbicide treatments is more difficult because of interactions with site preparation intensity and different treatment effects on survival and growth. It is clear that when herbicide use was combined with HSP, it gave a type C response with an early gain in production that was partially lost due to slowing of later growth (see below). When herbicide use was combined with LSP, the response was more of

Table 7
Parameter estimates, and summary statistics for mortality (percent of stems between ages 4 and 18) regressions with and without coefficient of variation for seedling growth at age 4 as independent variable[a]

	With CV (height)			Without CV (height)		
	Coefficient	Standard error	P-value	Coefficient	Standard error	P-value
Intercept	−57.202	8.92	<0.0001	0.037	9.46	0.99
Dominant height (m)	16.82	2.797	<0.0001	16.37	3.98	<0.0001
Dominant height growth (m)	−10.52	4.877	0.0337	−20.19	6.81	0.0039
Number of stems ha^{-1}	0.009	0.0026	0.0006	0.004	0.0036	0.2161
CV (height growth)	0.932	0.097	<0.0001	–	–	–
MSE	7.33			10.4		
CV (function)	44.2			60.8		
R^2	0.59			0.28		
n	92			92		

[a] Height and height growth for the 5% tallest trees at age 4, and number of stems at age 4 were also independent variables.

a type B with an early gain but no growth effect in the established stands. The combination of HSP and fertilization indicated a type A response with little early gain in volume growth but increased volume growth for the fertilized stand after crown closure. The combination of fertilization and LSP resulted in no fertilization effect at any time.

The early positive effects of intensive site preparation and herbicide treatment on growth were probably principally related to decreased competition from non-crop vegetation. Several studies have demonstrated the importance of controlling competing vegetation during the establishment phase (e.g. Britt et al., 1991; Fredericksen et al., 1991; Morris et al., 1993). On the same sites as in this study, Allen (1996) reported lower ground vegetation cover during the first growing season on HSP as compared to LSP. Vegetation cover was further decreased by the application of herbicides. However, when comparing treatments with and without herbicides within the HSP-treatment, treatments including herbicides showed higher mortality during the first 2 years as a direct result of herbicide damage. Allen and Lein (1998) and Quicke et al. (1999) concluded that this was due to the type and dosage of herbicides and that this negative effect is now avoidable with improved herbicide technology including chemical selection and application rates.

When comparing growth rates between LSP and HSP, growth was higher for HSP during the first 14 years after planting, indicating a long-term effect of the site preparation on resource availability. However, it is not likely that site preparation has increased long-term availability of nutrients since HSP on many sites involved a removal of nutrients. For a similar site, Tew et al. (1986) estimated the removal of N at about 650 kg ha^{-1} for shear, pile and disc as compared to 45 kg ha^{-1} for the less-intensive chop and burn. The corresponding figures for removal of P were about 40 and 0 kg ha^{-1} for shear, pile and disc, and chop and burn, respectively. Thus, a more probable cause for the increased growth is the effect that HSP had on competing hardwoods (Allen et al., 1990). When comparing shear, pile and disc to chop and burn, Fredericksen et al. (1991) found lower absolute volume of competing hardwoods in the shear, pile and disc treatment than in the chop and burn treatment. Furthermore, Glover and Zutter (1993) found that intensive site preparation (bulldozer) significantly reduced the basal area of competing hardwoods and that this reduction in competition from hardwoods resulted in a significant increase in loblolly pine yield 27 years after planting.

With HSP, volume growth on herbicide-treated plots was lower than for plots without herbicides during the last 4 years of this study (Fig. 2). One explanation for the reduced growth in herbicide-treated plots could be larger early losses of nutrients due to the herbicide treatment. Smethurst and Nambiar (1989) concluded that weeds may be useful in conserving N in the surface soil during the early phase of plantation establishment when the rate of N-uptake of trees is lower than the rate of net N-mineralized. In studies that included several of our sites, Vitousek and Matson (1985) and Vitousek et al. (1992) concluded that intensive site preparation and herbicide treatments could reduce N availability, increase the amount of N that could be potentially lost and extend the period over which such losses could occur.

Another reason for lower production in the herbicide-treated plots may have been higher mortality in terms of volume loss. The individual trees in these plots were larger as a result of lower stand density. This resulted in higher mortality in terms of volume since mortality was about equal in terms of number of stems. Mortality between years 14 and 18 on the herbicide treatment was 2.92 m^3 ha^{-1} per year while it was 2.04 m^3 ha^{-1} per year in the fertilized treatment. Thus, the difference in mortality does not make up for the 2.5 m^3 ha^{-1} per year difference in current annual increment, but if mortality is added to production, the difference between treatments was no longer statistically significant.

The LSP exhibited larger CV and a distinctly altered pattern in the development of CV as compared to HSP (Fig. 3). Variation in competition from hardwoods at different planting spots probably led to variation in growth which rapidly increased CV early in stand development. The later decrease in CV was probably due to mortality among the smallest trees which resulted in less variation in size among surviving trees. Since mortality in the LSP was only partly due to intraspecific competition between the planted loblolly pine trees, the discussion below will be restricted to stand development in the HSP.

When CVs among the various fertilization and herbicide treatments were compared at the same standing volume for HSP plots, the fertilization treatments had the lowest CV. However, this effect was only significant during the last years of the study and so the conditions during early stand development were probably not the cause for the differences in variability between tree sizes. Therefore, the herbicide and fertilization treatments could not be used to examine the hypothesis that decreased variability immediately after seedling establishment will slow self-thinning. Instead, we examined the variation that existed on all HSP plots. A regression function that included the variability in seedling growth between years 2 and 4 explained almost 60% of the mortality between years 4 and 18 while a corresponding regression function without these data accounted for only 28% of the variation in mortality. This indicates that variability in establishment of the planted seedlings did have a great importance for future stand development and especially future mortality. Thus, the hypothesis above was supported by data from this study, but there were insufficient differences in variability in seedling growth between the treatments for the herbicide and fertilization treatments to have a significant effect on stand development.

By 18 years, the advantages in early growth that were realized with herbicide use had diminished to the point where they were hard to recognize. However, imposition of intermediate-aged stand treatments such as thinning and/or fertilization that alleviate resource limitations may lead to a different result. Furthermore, mortality was high in the herbicide-treated plots as a result of herbicide damage. The mortality in the herbicide treatments may have resulted in a lesser volume growth response than what could have been achieved if survival had been higher. Quicke et al. (1999) found that volume gains due to herbicide treatments were higher for dense spacings than for more widely spaced stands. Thus, the long-term effects of herbicides may have been underestimated in this study.

If maintenance of maximum productivity during a rotation is the aim, it will be necessary to perform intermediate-aged silvicultural treatments to capitalize on the improved early growth rates that result from intensified regeneration efforts. For example, fertilization with N and P is typically needed to maintain good growth in loblolly pine stands in southeastern USA (Allen, 2001; Allen et al., 1990).

In conclusion, HSP improved long-term stand volume growth and it was suggested that the main long-term effect of the HSP was a reduction in competition from hardwoods. Herbicide and fertilization treatments at the time of planting did not improve long-term growth. There was an indication that the herbicide treatment reduced growth in the mature stand. Furthermore, this study showed that variability in establishment of planted seedlings did have a great importance for future stand development and especially future mortality. It was shown that variability in the seedling stand, as a result of intensive regeneration methods that reduces environmental heterogeneity, reduces the variability in the mature stands. However, because there were insufficient differences in variability in seedling growth between the herbicide and fertilization treatments, it could not be inconclusively proved that lower variability in the mature stands resulting from intensive regeneration treatments will result in reduced or postponed self-thinning.

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